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GROWTH RESPONSES OF GENETICALLY IMPROVED OPEN POLLENATED, FULL-SIBLING, AND CLONAL LOBLOLLY PINE TO THE FLEXSTAND^{TM} SILVICULTURAL SYSTEM

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GROWTH RESPONSES OF GENETICALLY IMPROVED OPEN POLLENATED, FULL-SIBLING, AND CLONAL LOBLOLLY PINE TO THE FLEXSTAND™ SILVICULTURAL SYSTEM

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ABSTRACT

Loblolly pine (*Pinus taeda*) is often listed as the most commercially important timber species in the southeastern United States and is subject to genetic improvement via breeding programs to increase sawtimber yield, stem quality, and disease resistance. ArborGen has trademarked the FlexStand™ Silvicultural System (a method of interplanting rows of genetically improved trees with less expensive biomass trees) as a more economical solution to growing Loblolly pine. Two studies were conducted to in order to assess the FlexStand™ Silvicultural System. The first study assessed seedling mortality and growth of four different genetic combinations were assessed in the first four growing seasons at the Johnson Experimental Forest. Full-sibling seedlings showed no significant differences in growth or survival in comparison to clones. Although full-sibling seedlings were initially significantly taller than open pollenated (OP) seedlings, growth rates were not significantly different. The second study assessed the growth characteristics of full-sibling trees arranged in FlexStands™ with elite OP biomass trees in comparison to monocultures in the ninth growing season. Full-sibling and OP monocultures had similar survival, diameter at breast height (DBH), height-to-live-crown, rust incidence, volume, and indices of competition. Full-sibling trees were significantly taller than the lowest grade OP trees, and had significantly less ramicorn branching and forking. In comparison to FlexStands™, full-sibling monocultures had significantly higher levels of competition due to closer spacing and significantly lower DBH. Stem quality, rust, ramicorn branching, forking, and volume did not differ significantly between full-sibling trees in monocultures and FlexStands™. These results suggest that the FlexStand™ is an economically advantageous option over monocultures, as volume and quality of trees sawtimber are the same as that of monocultures, but initial investment costs are lower in FlexStands™.

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TABLE OF CONTENTS

Page

Table of Contents (Continued)

LIST OF TABLES

LIST OF FIGURES

Figure Page

List of Figures (Continued)

Figure Page

List of Figures (Continued)

Figure Page

CHAPTER I
LITERATURE REVIEW

Introduction

Loblolly Pine (*Pinus taeda* L.) is one of the most commercially important and widely planted trees in the southeastern United States. Because of increasing demand in the lumber market, both commercial and private pine plantation owners are pressured to maximize production of high-quality sawtimber. However, many landowners find trade-off relationships between tree volume, quality, and rotation times. For example, an increase in volume requires increases in rotation times and thinning treatments. If a landowner wishes to maximize volume without sacrificing time, they may choose to use fertilizers and intensive thinnings to stimulate growth; however, wood quality may be sacrificed as increased growth rates may lead to an increase in growth defects. Overall, it can be difficult to maximize gains without sacrificing one of the three aforementioned factors.

However, since the 1950s there have been many advances in tree improvement programs. Companies such as ArborGen now use controlled methods of seedling production to ensure seedling buyers receive only the best genetically improved trees. There are several Loblolly pine "SuperTree" products that ArborGen markets with pricing based on the level of genetic improvement. The medium -priced Mass Control Pollinated (MCP) seedlings are the offspring of elite tree lineages. The parent trees were picked for their superior growth characteristics, including straightness of growth, height, resistance to pathogens, and lack of codominate apicals. ArborGen markets many other levels of genetically improved seedlings—

from their open pollinated varieties (OP) to their most expensive Elite Varietals—based on the needs and investment capital of landowners.

In addition to these genetically improved Loblolly pine seedling products, ArborGen also offers a number of silvicultural systems to help clients maximize productivity and economic gain from their pine plantations. The planting system in the focus of this review is the FlexStand™ Silvicultural System. This system dictates that two rows of genetically improved trees be planted simultaneously with one row of a genetically inferior biomass trees. When the stand reaches the thinning age, the biofuel trees will be removed and sold for pulpwood, leaving growing space for the genetically superior rows to develop. The benefits to this system are that; (1) the owner will not have to thin rows of expensive sawtimber trees, and (2) the biomass trees will provide a mid-rotation fiscal gain.

This review will examine the literature surrounding genetic improvements of Loblolly pine, seedling establishment, silvicultural treatments of Loblolly pine, and hardwood interactions with Loblolly pine plantations. The goal is to provide insight into whether or not these genetic improvements and planting systems may increase yield of sawtimber and economic gain.

The Importance of Loblolly Pine

Loblolly pine is the most commercially important and widespread pine species in the southeastern United States. It is estimated that Loblolly pine makes up 50% of standing pine and is the predominant pine on 13.7 million hectares (Ha) of commercial forest land in the southeast. It is capable of growing in a variety of site conditions. Loblolly pine can grow in both the upper and lower coastal plains of the southeast as well as the nutrient-drained soils of old fields of the Piedmont (Spring et al. 1974). The result of Loblolly pine's ability to grow in a variety of conditions is a large commercial range which spans from New Jersey to northern Florida and from the Coastal Plain to eastern Texas (Schultz 1997). While most Loblolly pine trees reach maturity at 80 years, they typically reach harvest size within 30 years, allowing for a short rotation period.

The combination of wide natural range, ability to grow in poor soil, and comparatively short rotation period makes Loblolly pine a commercially exploitable and quickly regenerative natural resource. Southern pine plantations increased in total acreage from 2 million acres to over 39 million acres from the 1950s to 2010 (Wear and Greis 2012). While nationwide timber production declined in the early 2000s, production in the Southeast was higher than any other region of the United States. Additionally, the total area planted pine area continues to increase despite the decline in overall production (Wear and Greis 2012).

Furthermore, development in silvicultural prescriptions such as planting, competition control, site prep, and timber stand improvement boosted productivity of southern pine plantations since the 1940s (Fox et al. 2007). Fertilizer and herbicide treatments have been shown to increase carbon allocation to the stem of recently established mid-rotation Loblolly pine (Edwards 1990, Albaugh et al. 2004, McKeand et al. 2006). Furthermore, mid-rotation thinning treatments greatly increased DBH, which is a critical factor affecting volume of sawtimber (Jokela et al. 2004, Roth et al. 2007a).

Tree Improvement and Common Loblolly Pine Growth Defects

Because of the high demand for Loblolly pine in the lumber market, landowners have taken several approaches to maximize production of sawtimber trees on their plantations. A sawtimber trees is defined as “A live tree of commercial species at least 9.0 inches d.b.h. for softwoods or 11.00 inches for hardwoods, containing at least one 12-foot sawlog or two noncontiguous 8-foot sawlogs, and meeting regional specifications for freedom from defect” (USDA Forest Service 2004). In order to meet these standards, the tree must have a straight trunk with minimal branching along the bole. Land managers can achieve straight, uniform growth in Loblolly pine by growing them in dense-rowed plantations. The planting density exploits the Loblolly pine’s shade-intolerant responses to competition and forces the trees to allocate carbon into vertical growth in order to minimize shading from competitors.

Furthermore, genetic improvements to Loblolly pine have been ongoing since the early 1950s. The two methods in the focus of this review are Mass Control Pollination (MCP) and Somatic Embryogenesis (Varietals). The products of both methods are marketed as elite genotypes from ArborGen; however there is a subtle, albeit major difference. The MCP seedlings are the offspring of pollinating the best female trees with the best male trees. Mass Control Pollination is accomplished by placing a physical barrier over the female strobili of the Loblolly pine, thereby preventing pollination by non-elite, wild genotypes. The bags are then inoculated with a hose containing the pollen of the desired genotype (Bramlett 1997). These MCP offspring are then planted in seed orchard and the straightest phenotypes with the largest DBHs and fewest defects are picked for plant tissue culture. The resulting clones are termed Varietals. Cumbie et al. found that there was an increase in quality of wood and sawtimber potential with genetic improvement. However, these genetic improvements come at a cost. The incidence of stem forking has been shown to be moderately correlated with increased diameter and height growth. Forking, though, was not correlated with sawtimber potential, meaning that the wood quality was more dependent on sweep and rust incidence (2007; 2012).

As previously mentioned, the best parents are selected based on desirable growth characteristics such as tallest height, largest DBH, straightest stems, resistance to fusiform rust (*Cronartium quercuum f.sp. fusiforme*), lack of ramicorn branching, as well as lack of stem forking. Current research of full-sibling loblolly pine indicates that height, DBH, and stem straightness are heritable traits (Baltunis et al. 2006, McKeand et al. 2006). Therefore, due to the additive nature of tree breeding, one might expect the DBH, height, and straightness to be greater in MCP and Cloned trees in comparison to open pollinated varieties. However, genetically improved trees also seem to be very sensitive to the environment conditions, with several of the same studies citing genotype x environment interactions effecting growth (Baltunis et al. 2006, McKeand et al. 2006, Roth et al. 2007a, Aspinwall et al. 2011). Therefore, site selection as well as genotype provenance should be carefully considered when deploying these genetically improved seedlings.

Research has been conducted to breed resistance to damaging agents such as Fusiform rust. Fusiform rust is a disease commonly found in loblolly pine caused by a fungal pathogen endemic to the southeastern United States, *Cronartium quercuum f.sp. fusiforme*. This fungus' life cycle begins in the leaves of host oak species, where urediospores develop on the leaf surface, causing pustules on the surface until telia develop on the bottom surface of the leaf. Teliospores then germinate to produce basidiospores. These basidiospores are then transported by air to pine trees, where they infect the cotyledons. The fungus then develops in the living tissue of the pine, which forms galls and produces aeciospores, which are then transferred back to oak trees where they develop into urediospores (Powers et al. 1981, Wilcox et al. 1996). The galls produced as a physiological response to Fusiform rust degrade wood quality and timber value. It has been estimated that rust resistance research and the use of rust resistant seedlings could return about $40-60 million to southern tree farmers per year (Cubbage and Pye 2000). While the complete decoding of the loblolly pine genome was completed in March of 2014, several studies have already identified the sites tied to rust resistance (Wilcox et al. 1996, Kubisiak et al. 2005, Li et al. 2006, Neale et al. 2014). Research supports that resistance to rust infection is not limited to a single locus, but two separate loci (Kayihan et al. 2005). These resistance traits appear to be heritable and additive (Isik et al. 2003). However, site characteristics are also important factors in rust resistance, as poor quality sites may stress trees and promote susceptibility to rust infection (McKeand et al. 2006).

The prevalence of stem defects has also been well documented, as stem forking and ramicorn branching can reduce the sawtimber volume of the tree. A ramicorn branch is defined as “a large, high-angled branch that often results when one member of a fork is partly suppressed by the more dominant member…when boards are sawn from a stem where a ramicorn originates, the resulting know is called a sucker knot.” (Helms 1998). Stem forks result when the codominant stem is not suppressed after the terminal leader has been damaged or killed (Howe 2006). Both ramicorn branches and stem forks result in the reduction of sawtimber volume and quality, as codominant stems generally do not reach saw log diameter and decrease the total number of saw logs a tree may produce. Furthermore, forks and ramicorns produce an irregular grain which is difficult to cut (Doede and Adams 1998). Thus these defects in the stem can have a significant effect on the economic value of a tree (Vargas-Hernandez et al. 2003). Most recent research indicates that ramicorn branching and forking may be controlled by the same genes, and therefore may be able to be improved together (Xiong et al. 2010).

Seedling establishment

The dominant method of establishment of loblolly pine stands in the southeastern United States is by planting seedlings. This method bypasses germination stages required by seed planting methods. It also reduces the amount of time needed to establish seedlings and increases survival rates, as seeds and newly germinated seedlings are very sensitive to microclimate fluctuations. While they are not as sensitive to fluctuations in the microclimate as seed-origin seedlings, planted seedlings are still sensitive to changes in the microclimate, as well as vulnerable to herbivory. Therefore, factors affecting the successful establishment of seedlings such as site preparation, planting density, herbaceous competition control, and tolerance to seasonal changes must be considered.

Site preparation is critical to seedling survival and growth. Site preparation may include: herbicide treatments to remove herbaceous species; mechanical treatments to incorporate logging residue into the soil, alter of soil structure to create beds for planting, and promote aeration. Research indicates the benefits of logging residue incorporation and fertilizer treatments to loblolly pine seedling growth by increasing soil carbon and nitrogen (Neary et al. 1990, Maier et al. 2012). Fertilizers have been shown to decrease root to shoot allocation ratios in seedlings. While this ratio change causes resources to be allocated to foliage and branching at the expense of root systems, the plant maintains the same photosynthetic rate (Stovall 2011). Furthermore, loblolly pine has been shown to change root to shoot allocation ratios with age due to strong ontogenetic processes (Aspinwall et al. 2011). This allocation ratio has also been shown to change within growing seasons due to weather fluctuations (Stovall et al. 2012). Therefore it may be pertinent to plan fertilizer treatments around allometric responses to maximize stem growth and minimize branch growth. Similarly, herbicide treatments to control herbaceous competition is effective in releasing seedlings from adjacent competing weeds, resulting in greater accumulation in biomass and greater vigor of seedlings (Britt et al. 1990, Edwards 1990).

Additionally, initial spacing of seedlings plays an important role in growth. As mentioned earlier, plantation trees are evenly spaced at a density that promotes height growth and gradual taper as opposed to sprawling growth and abrupt taper seen in open-grown trees. This is done to ensure the straightness of the trunk, as well as reduced the total number of branches. It is important economically because straight growth and minimal branching can maximize sawtimber yield, thereby maximizing profit from the stand. There have been numerous studies on the effects of planting density on various aspects of growth in loblolly pine. Although planting density has little effect on seedling growth in the first few years after planting (Zhao et al. 2011), it has been shown to increase total aboveground biomass, volume, total stand basal area, dominant and average tree height. The trees will allocate the more resources to the bole rather than to foliage and branches as the planting density increases (Subedi 2012; Zhao 2011; Anton-Fernandez et al. 2011).

However, higher planting densities (>2241 trees per Ha) were shown not to have significant differences in biomass allocation between stem, foliage, alive, and dead branches, regardless of culture intensity (Subedi et al. 2011, Zhao et al. 2012). Furthermore, while the lowest planting density resulted in higher average aboveground biomass allocation, the result was higher allocation in branches under both operational and intensive culture conditions. Conversely, the highest planting density resulted in the lowest average aboveground biomass allocation, but the highest percentage of biomass allocated to the stem under operational culture conditions (Subedi et al. 2011). These findings suggest the importance of planting density to biomass allocation to main stem, rather than to branches as increased branching can lead to the reduction of sawtimber value.

Furthermore, the condition of the planting stock also plays a critical role in initial survival and growth. Initial seedling root collar diameter size has been shown to increase initial gains on intensively managed plantations (South et al. 2001). Genetic improvement may also play a critical role in initial growth, but not survival (Baltunis et al. 2006). With seedlings of larger initial root collar diameter, genetic improvement, site preparation, and herbaceous control, planted loblolly pine seedlings can successfully survive and rapidly grow within the first few years of planting. Eventually these seedlings will outgrow herbaceous competitors and—if planted at the right density—be able to grow without unnecessary competitive stress until thinning age.

Interplanting Loblolly Pine and Sweetgum

There has been speculation that sweetgum (*Liquidambar styraciflua*) can be a successful biomass and biofuel tree (Wright and Cunningham 2008). It is a fast growing, pioneer hardwood that has been observed growing together with Loblolly pine in old-field succession (Bormann 1953). However, most studies that quantify the effects of intensive cultures or competitive interactions of sweetgum and loblolly pine are either: monocultures (Mou et al. 1995, Samuelson 1998); mixed plantings under accelerated growing periods in short-term studies (Groninger and Seiler 1995); or long-term studies that focus on dynamics of naturally regenerated pine and mixed hardwood stands (Glover and Zutter 1993). There is a paucity of literature examining the aboveground growth of the elite loblolly pine genotypes to interplantings of sweetgum in pine plantations. There are very few studies that specifically monitor the competitive effects of interplanted sweetgum on loblolly pine. The only study that was found suggested that loblolly had a linear competitive response in height, DBH, and volume to sweetgum. More so, loblolly pine had a more detectable competitive response to height with other loblolly pine, rather than with sweetgum (Perry et al. 1993). From these findings, it seems that loblolly pine will grow more competitively with conspecifics. However, more research must be done to evaluate stand productivity and wood quality from the elite genotypes interplanted with OP species

Stand Uniformity and Biomass Allocation-Limitations of Clonal Loblolly Pine

It is important to assess the growth uniformity and carbon allocation of genetically improved and cloned loblolly pine. Growth uniformity is important because it is linked with higher stand productivity, most likely due to more efficient light use as a product of an even canopy (Binkley et al. 2010, Aspinwall et al. 2011). Although many studies have quantified carbon allocation of both non-improved as well as improved genotypes of individually grown loblolly pine, there are few studies that examine effects of differences between levels of genetic input at stand-level carbon allocation as well as uniformity under operational conditions.

There have been studies, however, that note that stands of clonal loblolly pine show almost no difference in growth uniformity when compared to mixed genotype (OP) stands due to genotype x location interactions and fertilizer treatments (Roth et al. 2007b, Stovall et al. 2011, Aspinwall et al. 2011, Stovall and Carlson 2013). Furthermore, research suggests that the origin of cloned genotypes must be considered when planting on a site, as strong genotype x environment effects may be related to provenance. Differences in the genotype allometry were exhibited in short-term responses to fertilizer treatment (Stovall 2011), while other clone genotypes have variable levels of interaction with the planting site (Roth et al. 2007). Aspinwall et al. (2011) noticed significant amounts of phenotypic variation within stands of cloned loblolly pine. The study suggested that clonal stands may be more sensitive to the heterogeneity of the environment and exhibit more within-stand variation. Conversely, genetically heterogeneous (half-sib, OP) stands may be less sensitive to environmental heterogeneity and less stand variation (2011). This study concludes that under heterogeneous site conditions, pure stands of loblolly pine clones (i.e. Varietals) may not produce uniform stands and therefore not be as productive.

Under the appropriate silvicultural input, one can try to maximize productivity by homogenizing the land during site-preparation. Since loblolly pine has a very wide commercial range of varying site conditions and different provenances, one must carefully consider the cloned stand’s sensitivity to gradients in the environment. Alternatively, forest landowners may consider planting mixed stands of both clonal loblolly pine and full-sibling (MCP) genotypes. Although there has been no research into stand uniformity in a mixed genotype stand of loblolly pine, it may be a potential avenue for achieving a productive and valuable plantation.

Biomass allocation is an important factor in the development of genetically improved of Loblolly pine because different clonal families have been shown to allocate biomass differently. This is economically important to landowners because they will want to ensure that their sawtimber stands will allocate more biomass to the stems rather than to branches and foliage to reduce the incidence of stem defects. Biomass partitioning patterns have been shown to be significantly influenced by culture intensity, planting density, as well as fertilization regime in both short and long term trials (Stovall et al. 2011, 2012, Zhao et al. 2012, Subedi et al. 2012, Stovall and Carlson 2013).

Although many of these studies account for the responses and interactions of Loblolly pine to planting density, spacing, and cultural intensity, many of the studies focus on loblolly pine at a species level(Anton-Fernandez et al. 2011, Zhao et al. 2011, 2012, Subedi et al. 2012), and do not consider genotype. There needs to be more focus on the growth quality and biomass allocation of cloned- and mixed-genotype stands at an operational level. The few articles that address effects of genotype on loblolly pine at individual and stand level are written as part of the same study (Aspinwall et al. 2011a, 2011b, 2011c). Therefore, considering clone sensitivity to location and within-site environmental gradients will be pertinent to quantify the growth of elite genotypes of Loblolly pine under different environmental conditions as well as management strategies. The results of such a study will help elucidate the necessity of site-specific genotypes of elite loblolly pine and cultural prescriptions in achieving maximum sawtimber potential.

In conclusion, given the paucity of literature surrounding mixed-family plantings of genetically improved loblolly pines, it is pertinent to conduct a study that focuses on such a planting. The ArborGen FlexStand™ Sivicultural System is a method of interplanting rows of genetically improved, full-sibling loblolly pine (MCP trees) with lower quality, half-sibling or open pollenated loblolly pine, and even hardwood species such as sweetgum. ArborGen markets this silvicultural system as more feasible economically in comparison to monocultures due to mid-rotation thinning of the cheaper biomass stock. However, literature in this review suggests that there may be different levels of genetic sensitivities of growth characteristic in the establishment of seedlings, especially when considering sweetgum seedlings. Furthermore, these differences in growth rate and quality—over the time the stand developments—may produce a dominant canopy layer of MCP sawtimber trees with a suppressed layer of OP biomass trees. This could result in a reduction in volume of harvested at thinning, and may also result in considerable stem deformities in the sawtimber trees due to unsuppressed growth. Therefore, there is a need for research into the establishment and growth of these different genetically improved loblolly pine seedlings in the FlexStand™ Silvicultural system, as well as a mid-rotation study comparing the tree growth and quality of these same levels of genetic input.

CHAPTER II

SEEDLING ESTABLISHMENT AT JOHNSONEXPERIMENTAL FOREST

HYPOTHESES

We hypothesize that the superior genotypes of loblolly pine seedlings will show greater growth after the first four growing seasons after planting. However, we hypothesize that survivorship will not be dependent on genotype. Furthermore, we hypothesize planting arrangement (monocultures vs. FlexStands™) will not influence seedling growth in the first four years of growth.

OBJECTIVES

The purpose of this study was to: 1) quantify the survival of several genotypes of genetically improved loblolly pine and sweetgum seedlings after the first, second, third and fourth growing seasons, 2) quantify root collar diameter (RCD) and height growth of the genetically improved seedlings, 3) assess the aforementioned seedling survivorship and growth characteristics in ArborGen’s FlexStand™ Silviclutural System.

MATERIALS AND METHODS

Study Site Description

The seedling establishment trial is located in the Johnson Experimental Forest (JEF), a privately-owned land (owner, Knowlton Johnson) outside of Cheraw, South Carolina. This 91 hectare forest is divided into two tracts, referred to as the northern (72.14 hectares) and southern tracts (19.8 hectares), by Teals Mill Road and will be donated to the Clemson University Timberland Legacy Program to serve as a research and education resource for faculty and students. The loblolly pine seedling trials were located in two stands, one in each the northern and southern tract (Figure 1). In January 2010, 6.47 hectares from the southern, smaller tract (roughly 20.2 Ha) and the northern, larger tract (75.1 Ha), 13 hectares total, were clear-cut and replanted with an experimental trial of ArborGen's genetically improved loblolly pine. Chemical site prep consisted of 42oz/ac Garlon XRT, 3 qts/ac Accord XRT, and 32 oz/ac DLZ. The seedlings were obtained from ArborGen's South Carolina SuperTree Nursery located in Blenheim, SC.

Experimental Design

The seedlings of the Johnson Experimental Forest seedling trial were established in January 2010. The experimental design was a randomized complete block consisting of 4 treatment combination of 4 different genetic inputs. The genetic material consisted of: open pollenated loblolly pine bareroot seedlings, hereby known as OP; mass control pollenated loblolly pine bareroot seedlings, hereby referred to as MCP; clonal Loblolly pine varietal bareroot seedlings; and sweetgum bareroot seedlings.

These four genetic materials were arranged in four different treatments. The first treatment was a varietal OP FlexStand™, in which a row of OP was planted with one row clonal Loblolly pine varietal. The planting densities for the OP and varietals were 435 trees per acre (tpa) and 220 tpa, respectively. The second treatment was an MCP and Sweetgum flex, in which one row of Sweetgum was planted between every two rows of MCP. The planting densities for the Sweetgum and MCP were 340 tpa and 320 tpa, respectively. The third treatment consisted of an OP monoculture as a control planted at a density of 545 tpa. The fourth treatment consisted of a MCP monoculture planted at a density of 550 tpa. Since there were two treatments with two different genetic materials (the FlexStands™), there were six combinations of genetic input and treatment: the MCP seedlings in the MCP monoculture (MCPMCP), the MCP seedlings in the MCP/ Sweetgum FlexStand™ (MCPSGMCP), the OP seedlings in the OP monoculture (OPOP), the OP seedlings in the varietal/OP FlexStand™ (VROPOP) and the varietal seedlings in the varietal/OP FlexStand™ VROPVR.

Herbaceous control treatments in the southern tract consisted of broadcast 2oz/ac sulfometuron methyl in the MCP Sweetgum FlexStand™ and control OP stands in the southern tract, and Chopper in the Varietal OP FlexStand™ to control hardwood growth. The northern tract received 2oz/ac Oust band treatments in the MCP Sweetgum FlexStand™ to control herbaceous growth around the sweetgum, as well as spot treatments of Velpar to control oak establishment. 2oz/ac sulfumeturon methyl was used to control herbaceous growth where needed on the rest of the treatments. Although the herbicide treatments were not uniform in each treatment, the objective of hardwood and herbaceous management for each treatment was the same.

Two 20m x 20m sample plots were established in both blocks of each treatment (2 replicates of 4 treatments, 16 sampling plots total) in July and October of 2012. Seedling locations and mortality was assessed in August of 2012. Mortality assessments, root collar diameter, and height measurements of seedlings were taken in winter of 2012-2013 and resampled the following winter, 2013-2014.

Statistical Analysis

The randomized complete block design was analyzed with a General Linear Model (GLM) procedure on JMP (JMP®, Version *10.0.2*. SAS Institute Inc., Cary, NC, 1989-2007). Chi-square analysis was used to assess seedling survival. An ad-hoc Tukey's HSD test was used to compare the least square means in growth between treatments within the 3rd and 4th growing seasons (Northern Tract) as well as differences in growth between treatment within the 1st and 2nd growing seasons (Southern Tract). Although several treatments and genotypes had non-normal distributions, means were still compared, as residual errors had a normal distribution. Plots were created in R version 3.0.1 ggplot2 package (Wickham 2009, R Core Team 2014). Maps were created using ESRI ArcMap 10.1 (2011).

RESULTS

North Tract

The survival rate after the third growing season of MCP seedlings in the pure MCP treatment was 98.77% (n=80, α=0.95 CI [0.9333, 0.9978]). The survival rate after the third growing season for MCP seedlings in the MCPSG treatment was 100% (n=49, α=0.95 CI [0.9273, 1]). The survival rate after the third growing season for SG seedlings in the MCPSG treatment was 44.83% (n=16, α=0.95 CI [0.3755, 0.7458]). The survival rate after the third growing season for OP seedlings in the pure OP treatment was 100% (n=53, α=0.95 CI [0.9324, 1]). The survival rate after the third growing season for OP seedlings in the VROP treatment was 100% (n=15, α=0.95 CI [0.7961, 1]). The survival rate after the third growing season for VR seedlings in the VROP treatment was 100% (n=49, α=0.95 CI [0.9273, 1]). (Figure 1).

The height after the third growing season of MCP seedlings in the pure MCP treatment ranged from 22.0 cm to 92.0m, with a mean of 53.0 cm and standard deviation of 17.1 cm. The height after the third growing season of MCP seedlings in the MCPSG treatment ranged from 28.1 cm to 240.5 cm, with a mean of 142.8 cm and standard deviation of 47.3cm. The height after the third growing season for SG seedlings in the MCPSG treatment ranged from 48.3 cm to

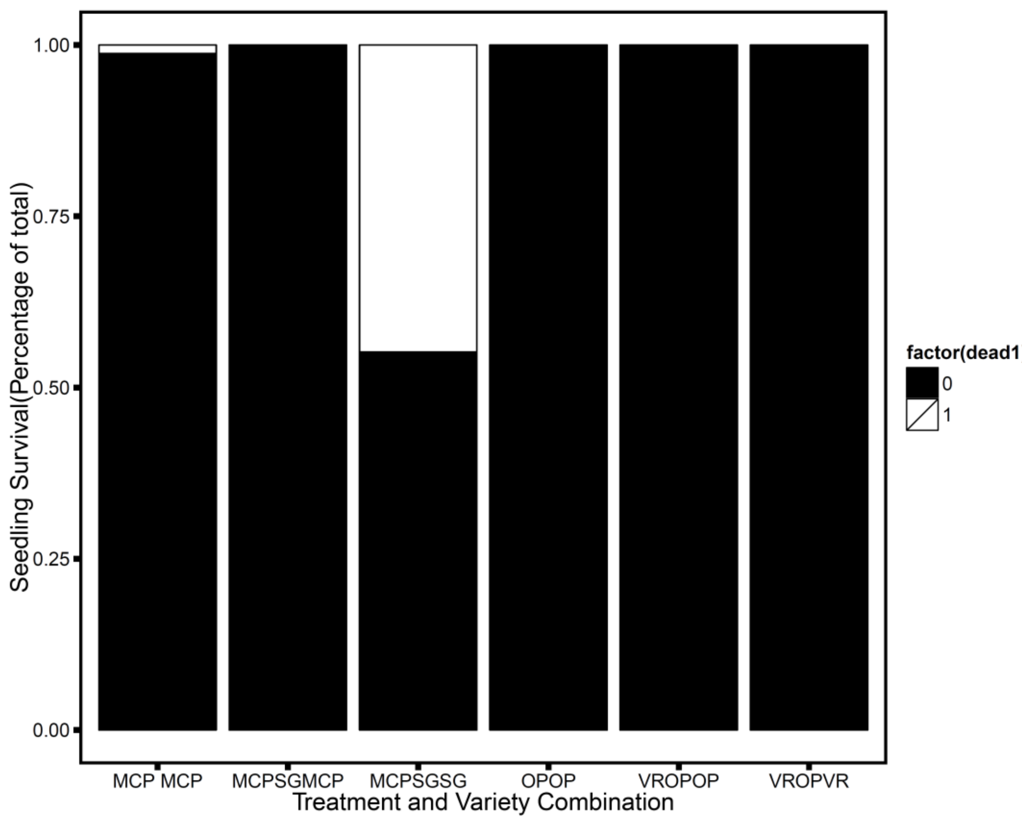

Figure 1. Seedling survival after the third growing season. Survival by treatment and genotype is shown as a percentage of total with dark bars as the percent alive.

215.5 cm, with a mean of 105.0 cm and a standard deviation of 39.6 cm. The height after the third growing season of OP seedlings in the control treatment ranged from 18.2 cm to 146.5 cm, with a mean of 59.8 cm and standard deviation of 36.8 cm. The height after the third growing season of the OP seedlings in the VROP treatment ranged from 17.3 cm to 113.5 cm, with a mean of 60.0 cm and standard deviation of 25.4 cm. The height after the third growing season of the VR seedling in the VROP treatment ranged from 26.1 cm to 173.1 cm with a mean of 84.7 cm and standard deviation of 35.9 cm (Table 1). Tukey's HSD comparison of the least square means suggest that the MCP seedlings in the MCPSG treatment (M=141.6 cm, SE=14.9 cm) were significantly taller after the third growing season than MCP seedlings (M=53.0 cm, SE=14.9 cm) in monoculture. The height VR seedlings in the VROP treatment (M=87.5 cm, SE=14.9 cm), OP seedlings in the VROP treatment (M=60.5 cm, SE=14.9 cm), and OP seedlings in the control (M=65.3 cm, SE=14.9 cm) were not significantly different from the other treatments.

The RCD after the third growing season for the MCP seedlings in the pure MCP treatment ranged from 4.91 mm to 27.44 mm with a mean of 11.49 mm and a standard deviation of 4.90 mm. The RCD after the third growing season of MCP seedlings in the MCPSG treatment ranged from 12.73 mm to 58.9mm, with a mean of 34.33 mm and a standard deviation of 10.93 mm. The RCD after the third growing season of SG seedlings in the MCPSG treatment ranged from 8.73 mm to 39.57 mm, with a mean of 19.03 mm and standard deviation of 6.93 mm. The RCD after the third growing season of OP seedlings in the control treatment ranged from 5.65 mm to 37.97 mm, with a mean of 15.55 mm and a standard deviation of 9.75 mm. The third growing RCD of OP seedlings in the VROP treatment ranged from 5.42 mm to 22.29 mm, with a mean of 12.20 mm and a standard deviation of 5.07 mm. The RCD after the third growing season of the VR seedlings in the VROP treatment ranged from 6.06 mm to

Table 1. Mean seedling height and root collar diameter after the third growing season.

		Height Year 3 (cm)		RCD Year 3 (mm)	
Treatment/Genotype	N	Mean	Std Dev	Mean	Std Dev
MCP/MCP	80	52.99875	17.06079	11.48717	4.903096
MCPSG/MCP	49	142.8245	47.29544	34.33299	10.93064
MCPSG/SG	29	105.0138	39.55411	19.03793	6.928099
OP/OP	53	59.81321	36.83328	15.55088	9.754766
VROP/OP	15	59.96667	25.36318	12.19511	5.067422
VROP/VR	49	84.67571	35.95708	19.42463	11.07146

49.20mm, with a mean of 19.42mm and standard deviation of 11.07mm (Table 1). Tukey's HSD comparisons of the least square means of RCD after the third growing season suggest that there were no significant differences between the MCP seedlings in the MCPSG treatment (M=33.51mm, SE=4.14 mm), the VR seedlings in the VROP treatment (M=20.15 mm, SE=4.14 mm), the OP seedlings in the control (M=16.97 mm, SE=4.14 mm), the OP seedlings in the VROP treatment (M=12.55 mm, SE=4.14 mm), or the MCP seedlings in monoculture (M=11.48 mm, SE=4.14 mm).

The survival rate after the fourth growing season of MCP seedlings in the pure MCP treatment was 95.06% (n=77, α=0.95 CI [0.8797, 0.9806]). The survival rate after the fourth growing season for MCP seedlings in the MCPSG treatment was 100% (n=49, α=0.95 CI [0.9273, 1]). The survival rate after the fourth growing season for SG seedlings in the MCPSG treatment was 0% (n=29, α=0.95 CI [0.8830, 0.9500]). The survival rate after the fourth growing season for OP seedlings in the pure OP treatment was 88.68% (n=47, α=0.95 CI [0.7742, 0.9470]). The survival rate after the fourth growing season for OP seedlings in the VROP treatment was 100% (n=15, α=0.95 CI [0.7961, 1]). The survival rate after the fourth growing season for VR seedlings in the VROP treatment was 100% (n=49, α=0.95 CI [0.9273, 1]) (Figure 2).

The height after the fourth growing season of MCP seedlings in the pure MCP treatment ranged from 31.5 cm to 274.5cm, with a mean of 109.5 cm and standard deviation of 44.5 cm. The height after the fourth growing season of MCP seedlings in the MCPSG treatment ranged from 102.7 5cm to 326.5cm, with a mean of 241.5 cm and standard deviation of 52.3cm. The height after the fourth growing season for SG seedlings in the MCPSG treatment ranged from 47.5 cm to 193.7 cm, with a mean of 104.5 cm and a standard deviation of 37.1 cm. The height after the fourth growing season of OP seedlings in the control treatment ranged from

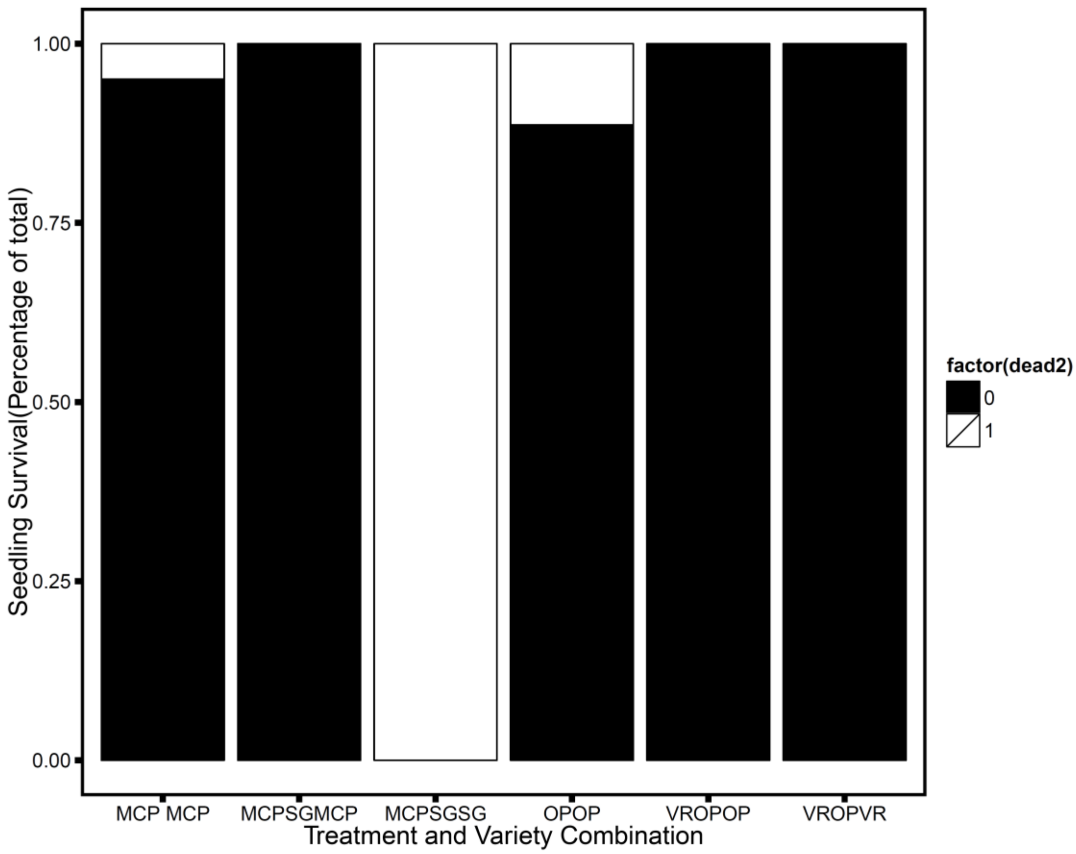

Figure 2. Seedling survival after the fourth growing season. Survival by treatment and genotype is shown as a percentage of total with dark bars as the percent alive.

53.5cm to 277.8 cm, with a mean of 128.23cm and standard deviation of 62.1 cm. The height after the fourth growing season of the OP seedlings in the VROP treatment ranged from 63.25 cm to 191.75 cm, with a mean of 100.5 cm and standard deviation of 34.1cm. The height after the fourth growing season of the VR seedling in the VROP treatment ranged from 69.0 cm to 315.3 cm with a mean of 155.2 cm and standard deviation of 64.6 cm (Table 2). Tukey's HSD comparison of the least square means suggests that the MCP seedlings in the MCPSG treatment (M=238.8 cm, SE=21.2 cm) were significantly taller than the MCP seedlings in monoculture (M=109.3 cm, SE=21.2 cm), as well as the OP seedlings in the VROP treatment (M=101.7 cm, SE=21.2cm). The height in the fourth growing season of the VR seedlings in the VROP treatment (M=158.7cm, SE=21.2cm), as well as the OP seedlings in monoculture (M=122.6 cm, SE=21.2cm) were not significantly different from any of the other treatments.

The RCD after the fourth growing season for the MCP seedlings in the pure MCP treatment ranged from 8.98 mm to 65.36mm with a mean of 26.23mm and a standard deviation of 11.60mm. The RCD after the fourth growing season of MCP seedlings in the MCPSG treatment ranged from 27.31mm to 96.91mm, with a mean of 62.66 mm and a standard deviation of 15.63mm. The RCD after the fourth growing season of SG seedlings in the MCPSG treatment ranged from 0.76mm to 31.12mm, with a mean of 17.88mm and standard deviation of 6.60mm. The RCD after the fourth growing season of OP seedlings in the control treatment ranged from 10.09mm to 63.99mm, with a mean of 32.41mm and a standard deviation of 17.05mm. The RCD of OP seedlings in the VROP treatment after the fourth growing season ranged from 11.51mm to 40.04mm, with a mean of 27.07mm and a standard deviation of 9.25mm. The RCD after the fourth growing season of the VR seedlings in the VROP treatment ranged from 12.81 mm to 90.08mm, with a mean of 39.93mm and standard deviation of

Table 2. Mean seedling height and root collar diameter after the fourth growing season.

		Height Year 4 (cm)		Diameter Year 4 (mm)	
Treatment/Genotype	N	Mean	Std Dev	Mean	Std Dev
MCP/MCP	80	109.5	44.6	26.23	11.60
MCPSG/MCP	49	241.5	52.3	62.66	15.63
MCPSG/SG	25	104.5	37.1	17.88	6.60
OP/OP	53	114.5	55.1	28.18	15.54
VROP/OP	15	100.5	34.1	27.07	9.25
VROP/VR	49	155.2	64.6	39.93	18.96

18.96mm (Table 2). Tukey's HSD comparison of the least square mean suggest that there were no significant differences in RCD after the fourth growing season between the MCP seedlings in the MCPSG treatment (M=61.80 mm, SE=6.45 mm), the VR seedlings in the VROP treatment (M=41.22mm, SE=6.45mm)the OP seedlings in the control (M=30.33 mm, SE=6.45 mm), the OP seedlings in the VROP treatment (M=27.62 mm, SE=6.45 mm), or the MCP seedlings in monoculture (M=26.18 mm, SE=6.45mm).

The difference in height between the third and fourth growing seasons of MCP seedlings in the pure MCP treatment ranged from -6.0 cm to 246.5 cm, with a mean of 57.3 cm and a standard deviation of 36.8 cm. The difference in height between the third and fourth growing seasons of MCP seedlings in the MCPSG treatment ranged from 12.1 cm to 234.5 cm, with a mean of 98.7 cm and standard deviation and 39.20 cm. The difference in height between the third and fourth growing seasons of OP seedlings in the control treatment ranged from 22.7 cm to 242.3cm, with a mean of 102cm and standard deviation of 65.03 cm. The difference in height between the third and fourth growing seasons of OP seedling in the VROP treatment ranged from 17.6 cm to 192.15 cm, with a mean of 61.2 cm and standard deviation of 29.3 cm. The difference in height between the third and fourth growing seasons of VR seedlings in the VROP treatment ranged from -0.5cm to 209.1cm, with a mean of 70.6 cm and standard deviation of 40.1cm (Table 3) (Figure 3). Tukey's HSD comparison of the least square means suggest that the MCP seedlings in the MCPSG (M=97.2 cm, SE=7.85 cm) had significantly more growth in comparison to the OP seedling in the VROP treatment (M=41.1 cm, SE=7.85 cm). The height growth of the VR seedlings in the VROP treatment (M=71.2 cm, SE=7.85 cm), the OP seedlings in the control (M=64.1 cm, SE=7.85 cm), as well as the MCP seedlings in monoculture (M=57.3 cm, SE=7.85 cm) were not significantly different from the other treatments.

Table 3. Mean seedling height growth and root collar diameter growth between years three and four.

		Height Growth (cm)		RCD Growth (mm)	
Treatment/Genotype	N	Mean	Std Dev	Mean	Std Dev
MCP/MCP	80	57.6	36.8	15.15	8.70
MCPSG/MCP	49	98.7	39.2	28.33	6.68
OP/OP	53	61.2	33.4	13.84	8.38
VROP/OP	15	40.6	29.3	14.88	6.00
VROP/VR	49	70.6	40.1	20.51	10.36

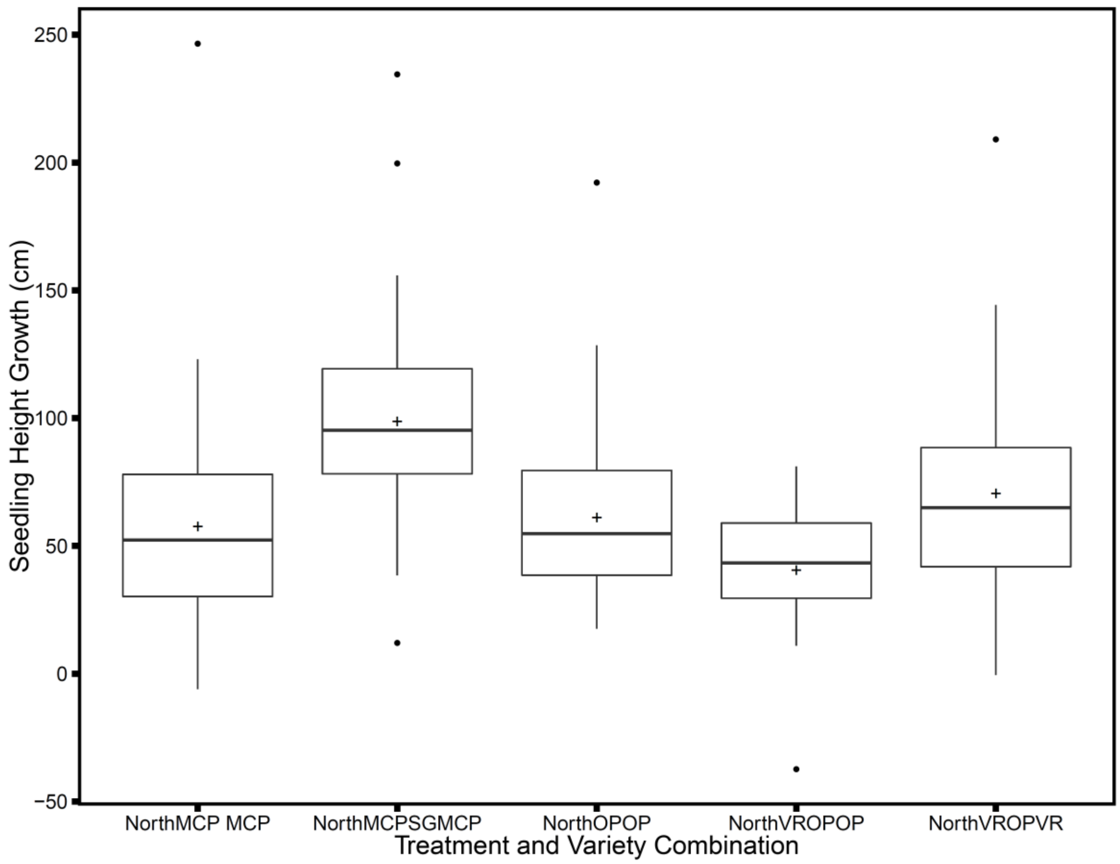

Figure 3. Seedling height growth from the Northern tract (third to fourth growing season) by treatment and variety combination. The box plot shows the mean (+), median (Q_2), 25th percentile (Q_1), and 75th percentile (Q_3) as well as outliers (dots). Outliers are defined as values greater than Q_3+ 1.5 IQR (interquartile range) or less than Q1-1.5IQR.

The difference in RCD between the third and fourth growing seasons of MCP seedlings in the pure MCP treatment ranged from 3.00 mm to 60.45mm, with a mean of 15.15 mm and standard deviation of 8.70 mm. The difference in RCD between the third and fourth growing seasons of the MCP seedlings in the MCPSG treatment ranged from 7.28 mm to 43.47 mm, with a mean of 28.33 mm and standard deviation of 6.68 mm. The difference in RCD between the third and fourth growing seasons of the OP seedlings in the control treatment ranged from 1.21 mm to 32.69 mm, with a mean of 13.84 mm and standard deviation of 8.38 mm. The difference in RCD between the third and fourth growing seasons of the OP seedlings in the VROP treatment ranged from 4.93 mm to 26.38 seedlings, with a mean of 14.88 mm and standard deviation of 6.00mm. The difference in RCD between the third and fourth growing seasons of the VR seedlings in the VROP treatment ranged from 4.09 mm to 41.17 mm, with a mean of 20.51 mm and standard deviation of 10.36mm (Table 3) (Figure 4). Tukey's HSD comparison of the least square means suggest that there were no significant difference in RCD growth between MCP seedlings in the MCPSG treatment (M=28.28mm, SE=2.44 mm), the VR seedlings in the VROP treatment (M=21.07 mm, SE=2.44 mm), the OP seedlings in the control (M=14.52 mm, SE=2.44 mm), the OP seedlings in the VROP treatment (M=15.07 mm, SE=2.44 mm), or the MCP seedlings in monoculture (M=15.11 mm, SE=2.44 mm).

South Tract

The survival rate after the first growing season of the MCP seedlings in the pure MCP treatment was 97.5% (n=39, α=0.95 CI [0.8712, 0.9956]). The survival rate after the first growing season of MCP seedlings in the MCPSG treatment was 41.86% (n=18, α=0.95 CI [0.2838, 0.5667]). The survival rate after the first growing season of SG seedlings in the MCPSG treatment was 44.44% (n=24, α=0.95 CI [0.3200, 0.5762]). The survival rate after the first

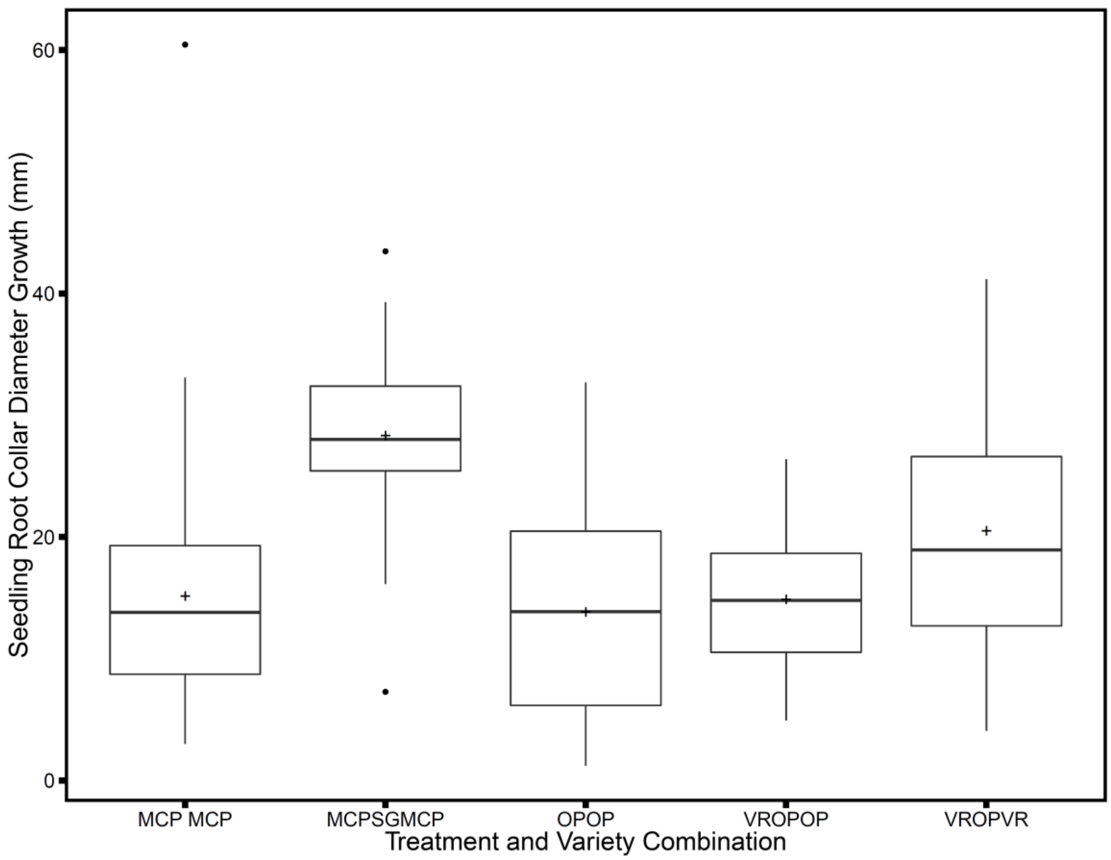

Figure 4. Seedling root collar diameter growth from northern tract (third to fourth growing season) by treatment and variety combination. The box plot shows the mean (+), median (Q_2), 25th percentile (Q_1), and 75th percentile (Q_3) as well as outliers (dots). Outliers are defined as values greater than Q_3+ 1.5 IQR (interquartile range) or less than Q1-1.5IQR.

growing season of OP seedlings in the control treatment was 100% (n=62, α=0.95 CI [0.9416, 1]). The survival rate after the first growing season of OP seedlings in the VROP treatment was 100% (n=18, α=0.95 CI [0.8241, 1]). The survival rate after the first growing season of VR seedling in the VROP treatment was 97.29% (n=36, α=0.95 CI [0.8618, 0.9952]). (Figure 5)

The height of the MCP seedlings in the pure MCP treatment after the first growing season ranged from 15.2 cm to 144.1 cm, with a mean of 33.1 cm and standard deviation 20.2 cm. The height of the MCP seedlings in the MCPSG treatment after the first growing season ranged from 27.2 cm to 94.2cm, with a mean of 55.7 cm and standard deviation of 17.26 cm. The height of the SG seedlings in the MCPSG treatment after the first growing season ranged from 27.4 cm to 114.8 cm, with a mean of 63.1 cm and standard deviation of 17.6 cm. The height of the OP seedlings in the control treatment after the first growing season ranged from 18.2 cm to 71.8 cm, with a mean of 37.5 cm and standard deviation of 12.4 cm. The height of the OP seedlings in the VROP treatment after the first growing season ranged from 22.4 cm to 87.3 cm, with a mean of 35.9 cm and standard deviation of 14.1 cm. The height of VR seedlings in the VROP treatment after the first growing season ranged from 42.3 cm to 101.0 cm, with a mean of 56.5 cm and standard deviation of 13.0 cm (Table 4). Tukey's HSD of the least square means results suggest the height of SG seedlings in the MCPSG treatment (M=62.9 cm, SE=3.3 cm), the VR seedlings in the VROP seedlings (M=56.34 cm, SE=3.3 cm), as well as the MCP seedlings in the MCPSG treatment (M=55.4 cm, SE=3.3 cm) were not significantly different. These seedlings however, were significantly taller than OP seedlings in the VROP treatment (M=36.1 cm, SE=3.3 cm), OP seedlings in the control (M=35.1 cm, SE=3.3 cm), as well as the MCP seedlings in monoculture (M=33.7 cm, SE=3.3 cm).

The RCD after the first growing season for the MCP seedlings in the pure MCP treatment

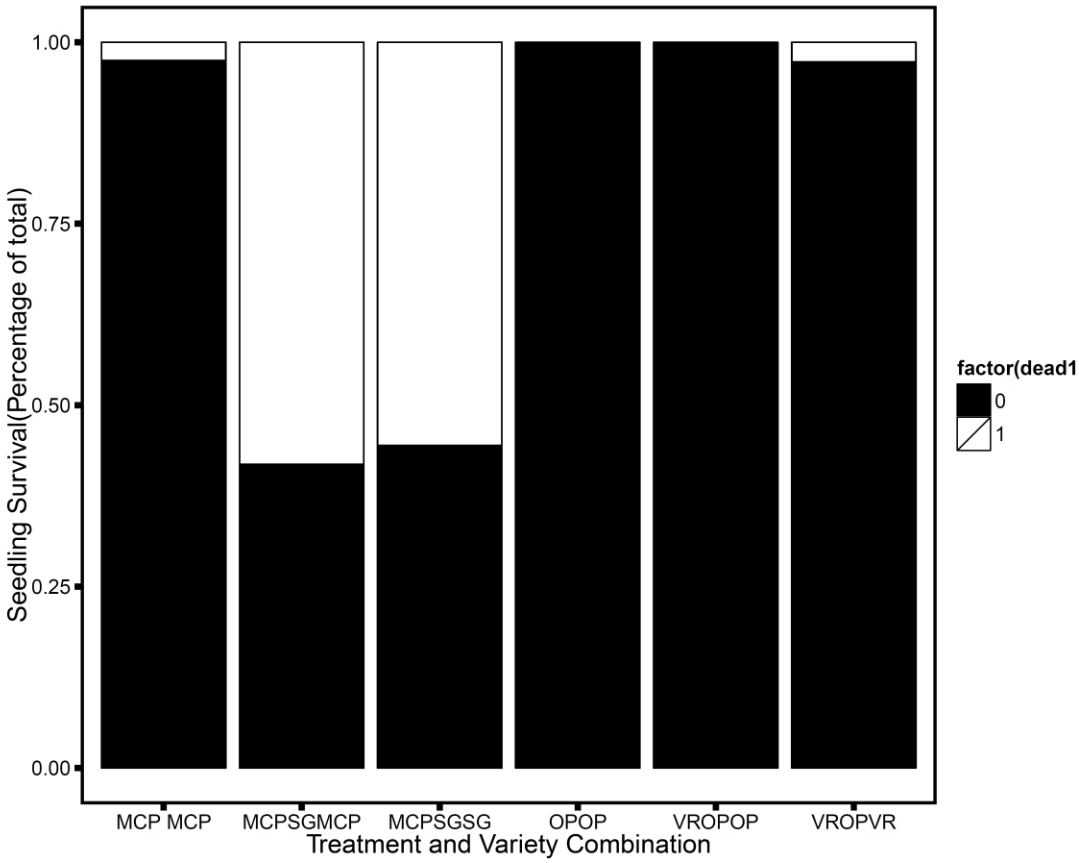

Figure 5. Seedling survival after the first growing season. Survival by treatment and genotype is shown as a percentage of total with dark bars as the percent alive.

ranged from 3.18 mm to 13.51 mm with a mean of 8.36 mm and a standard deviation of 2.29 mm. The RCD after the first growing season of MCP seedlings in the MCPSG treatment ranged from 4.92 mm to 17.90mm, with a mean of 10.33 mm and a standard deviation of 3.28 mm. The RCD after the first growing season of SG seedlings in the MCPSG treatment ranged from 5.77 mm to 19.60 mm, with a mean of 10.85 mm and standard deviation of 3.02mm. The RCD after the first growing season of OP seedlings in the control treatment ranged from 5.43 mm to 18.46 mm, with a mean of 9.09 mm and a standard deviation of 2.87 mm. The first growing RCD of OP seedlings in the VROP treatment ranged from 5.31 mm to 12.40 mm, with a mean of 9.51mm and a standard deviation of 2.06 mm. The RCD after the first growing season of the VR seedlings in the WROP treatment ranged from 9.70 mm to 23.60mm, with a mean of 15.50 mm and standard deviation of 3.76 mm (Table 4). Tukey's HSD comparison of the least square means suggest that the VR seedlings in the VROP treatment (M=15.6 mm, SE=0.79 mm) had a significantly larger RCD than the SG seedlings in the MCPSG treatment (M=10.8315.6 mm, SE=0.79 mm), the MCP seedlings in the MCPSG treatment (M=10.29 mm, SE=0.79 mm), the OP seedlings in the VROP treatment (M=9.57 mm, SE=0.79 mm), the OP seedlings in monoculture (M=8.50 mm, SE=0.79 mm), and the MCP seedlings in monoculture (M=7.9mm, SE=0.79 mm).

The survival rate after the second growing season of MCP seedlings in the pure MCP treatment was 97.56% (n=39, α=0.95 CI [0.8712, 0.9955]). The survival rate after the second growing season for MCP seedlings in the MCPSG treatment was 41.86% (n=18, α=0.95 CI [0.2838, 0.5667]). The survival rate after the second growing season for SG seedlings in the MCPSG treatment was 42.59% (n=23, α=0.95 CI [0.3033, 0.5584]). The survival rate after the second growing season for OP seedlings in the pure OP treatment was 98.39% (n=61, α=0.95 CI [0.9141, 0.9971]). The survival rate after the second growing season for OP seedlings in the

Table 4. Mean seedling height and root collar diameter after the first growing season.

		Height Year 1 (cm)		RCD Year 1 (mm)	
Treatment/Genotype	N	Mean	Std Dev	Mean	Std Dev
MCP/MCP	40	33.1	20.2	8.36	2.29
MCPSG/MCP	41	55.7	17.3	10.33	3.28
MCPSG/SG	52	63.1	17.6	10.85	3.02
OP/OP	62	37.5	12.4	9.09	2.87
VROP/OP	18	35.9	14.1	9.52	2.06
VROP/VR	37	56.5	13.0	15.50	3.76

VROP treatment was 100% (n=18, α=0.95 CI [0.8241, 1]). The survival rate after the second growing season for VR seedlings in the VROP treatment was 97.30% (n=36, α=0.95 CI [0.8618, 0.9952]) (Figure 6).

The height after the second growing season of MCP seedlings in the pure MCP treatment ranged from 15.25 cm to 210.3 cm, with a mean of 126.3 cm and standard deviation of 43.1 cm. The height after the second growing season of MCP seedlings in the MCPSG treatment ranged from 43.75 cm to 293.0 cm, with a mean of 163.9 cm and standard deviation of 67.8cm. The height after the second growing season for SG seedlings in the MCPSG treatment ranged from 68.75 cm to 206.0 cm, with a mean of 128.6 cm and a standard deviation of 30.9 cm. The height after the second growing season of OP seedlings in the control treatment ranged from 61.0 cm to 207.5 cm, with a mean of 135.6 cm and standard deviation of 39.5 cm. The height after the second growing season of the OP seedlings in the VROP treatment ranged from 21.5 cm to 204.5 cm, with a mean of 131.1 cm and standard deviation of 42.7 cm. The height after the second growing season of the VR seedling in the VROP treatment ranged from 23.5 cm to 269.5 cm with a mean of 151.0 cm and standard deviation of 61.27 cm (Table 5). Tukey's HSD comparison of the least square means suggest that there were no significant differences in height after the second growing season between the SG seedlings in the MCPSG treatment (M=157.2 cm, SE=31.9 cm), the VR seedlings in the VROP treatment (M=149.5 cm, SE=31.9 cm), the OP seedlings in the VROP treatment (M=134.5 cm, SE=31.9 cm), the OP seedlings in monoculture (M=131.3 cm, SE=31.9 cm), the MCP seedlings in the MCPSG treatment (M=122.2 cm, SE=31.9 cm), and the MCP seedlings in monoculture (M=116.3 cm, SE=31.9 cm).

The RCD after the second growing season for the MCP seedlings in the pure MCP treatment ranged from 8.73 mm to 48.08 mm with a mean of 33.87 mm and a standard

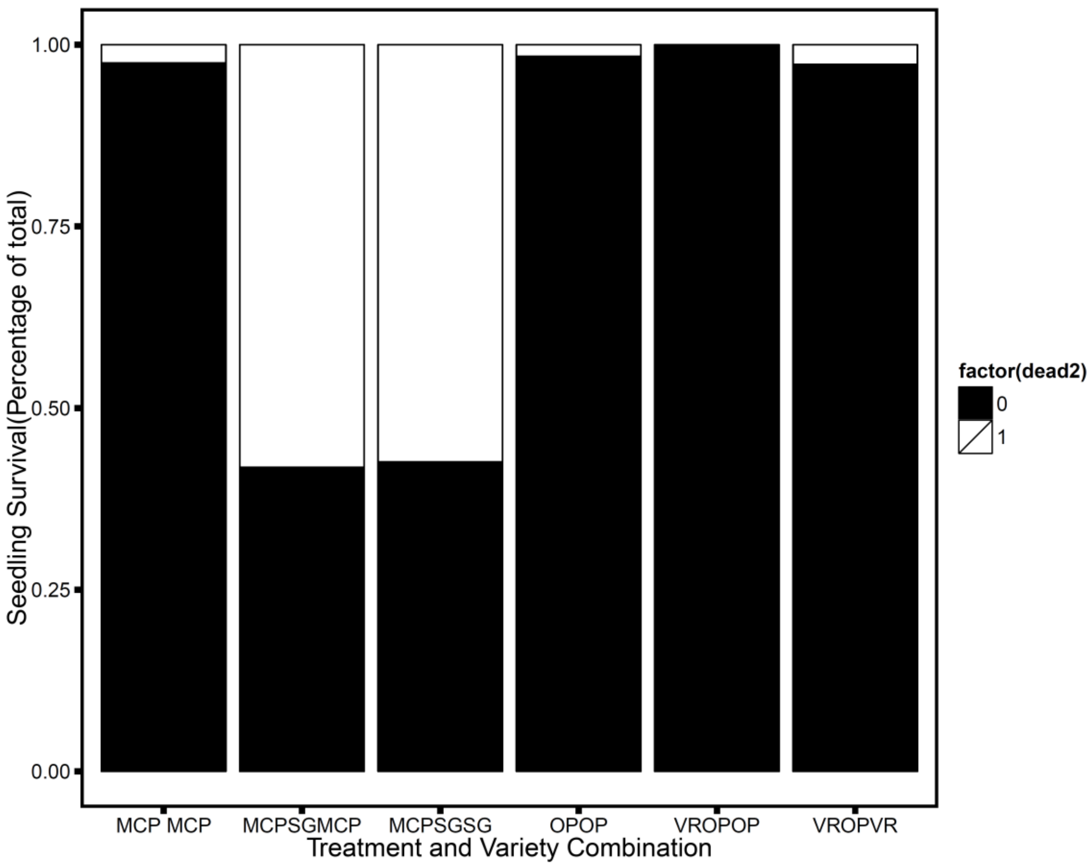

Figure 6. Seedling survival after the second growing season. Survival by treatment and genotype is shown as a percentage of total with dark bars as the percent alive.

deviation of 9.58 mm. The RCD after the second growing season of MCP seedlings in the MCPSG treatment ranged from 21.87 mm to 59.86 mm, with a mean of 38.61 mm and a standard deviation of 10.76 mm. The RCD after the second growing season of SG seedlings in the MCPSG treatment ranged from 14.06 mm to 37.24 mm, with a mean of 24.57 mm and standard deviation of 7.48 mm. The RCD after the second growing season of OP seedlings in the control treatment ranged from 15.27 mm to 51.14 mm, with a mean of 33.09 mm and a standard deviation of 8.69 mm. The second growing RCD of OP seedlings in the VROP treatment ranged from 10.96 mm to 52.09 mm, with a mean of 33.57 mm and a standard deviation of 10.40 mm. The RCD after the second growing season of the VR seedlings in the VROP treatment ranged from 22.68mm to 60.2 mm, with a mean of 38.88 mm and standard deviation of 8.92 mm (Table 5). Tukey's HSD of the least square mean suggest that there were no significant differences in RCD after the second growing season between the VR seedlings in the VROP treatment (M=38.75 mm, SE=5.29 mm), the OP seedlings in the VROP treatment (M=33.81 mm, SE=5.29 mm), the MCP seedlings in the MCPSG treatment (M=30.73 mm, SE=5.29 mm), the OP seedlings in the control (M=30.48 mm, SE=5.29 mm), the MCP seedlings in monoculture (M=30.03 mm, SE=5.29 mm), and the SG seedlings in the MCPSG treatment (M=26.09 mm, SE=5.29 mm).

The difference in height between the first and second growing seasons of MCP seedlings in the pure MCP treatment ranged from -33.6 cm to 157.8 cm, with a mean of 91.5 cm and a standard deviation of 43.6 cm. The difference in height between the first and second growing seasons of MCP seedlings in the MCPSG treatment ranged from -2.2 cm to 215.6 cm, with a mean of 91.6 cm and standard deviation and 43.59 cm. The difference in height between the first and second growing seasons of OP seedlings in the control treatment ranged from 37.4 cm to 129.3 cm, with a mean of 103.4 cm and standard deviation of 33.4 cm. The difference in

Table 5. Mean seedling height and root collar diameter after the second growing season.

		Height Year 2 (cm)		Diameter Year 2 (cm)	
Treatment/Genotype	N	Mean	Std Dev	Mean	Std Dev
MCP/MCP	39	125.0	42.9	32.87	9.58
MCPSG/MCP	20	163.9	67.8	38.61	10.76
MCPSG/SG	24	128.6	30.9	24.57	7.48
OP/OP	61	141.6	39.0	33.09	8.69
VROP/OP	18	131.1	42.7	33.57	10.40
VROP/VR	36	150.9	61.3	38.88	8.92

height between the first and second growing seasons of OP seedling in the VROP treatment ranged from -0.9 cm to 176.1 cm, with a mean of 95.2 cm and standard deviation of 40.8 cm. The difference in height between the first and second growing seasons of VR seedlings in the VROP treatment ranged from -25.0 cm to 187.5 cm, with a mean of 94.06 cm and standard deviation of 54.3 cm (Table 6) (Figure 7). Tukey's HSD comparison of the least square means suggest that there were no significant differences in height growth between the OP seedlings in the VROP treatment (M=98.4 cm, SE=31.3 cm), the OP seedlings in the control (M=96.1 cm, SE=31.3 cm), the VR seedling in the VROP treatment (M=92.8 cm, SE=31.3 cm), the SG seedlings in the MCPSG treatment (M=82.1 cm, SE=31.3 cm), the MCP seedlings in monoculture (M=81.9 cm, SE=31.3 cm), and the MCP seedlings in the MCPSG treatment (M=63.1 cm, SE=31.3 cm).

The difference in RCD between the first and second growing seasons of MCP seedlings in the pure MCP treatment ranged from 4.11 mm to 37.21 mm, with a mean of 24.38 mm and standard deviation of 8.04 mm. The difference in RCD between the first and second growing seasons of the MCP seedlings in the MCPSG treatment ranged from 7.5 mm to 42.93 mm, with a mean of 28.23 mm and standard deviation of 8.79 mm. The difference in RCD between the first and second growing seasons of the SG seedlings in the MCPSG treatment ranged from 3.06 mm to 25.56 mm, with a mean of 14.52 mm and standard deviation of 6.60 mm. The difference in RCD between the first and second growing seasons of the OP seedlings in the control treatment ranged from 9.85 mm to 38.53 mm, with a mean of 23.95 mm and standard deviation of 6.75 mm. The difference in RCD between the first and second growing seasons of the OP seedlings in the VROP treatment ranged from 4.38 mm to 39.69mm, with a mean of 24.05 mm and standard deviation of 8.73 mm. The difference in RCD between the first and second growing seasons of the VR seedlings in the VROP treatment ranged from 7.30 mm to 40.35 mm, with a mean of

Table 6. Mean seedling height growth and root collar diameter growth between years one and two.

		Height Growth (cm)		RCD Growth (cm)	
Treatment/Genotype	N	Mean	Std Dev	Mean	Std Dev
MCP/MCP	39	91.6	43.6	24.38	8.04
MCPSG/MCP	20	121.2	51.2	28.29	8.80
MCPSG/SG	24	71.4	22.6	14.52	6.60
OP/OP	61	104.0	33.4	23.95	6.75
VROP/OP	18	95.2	40.8	24.05	8.73
VROP/VR	36	94.1	54.3	23.26	7.61

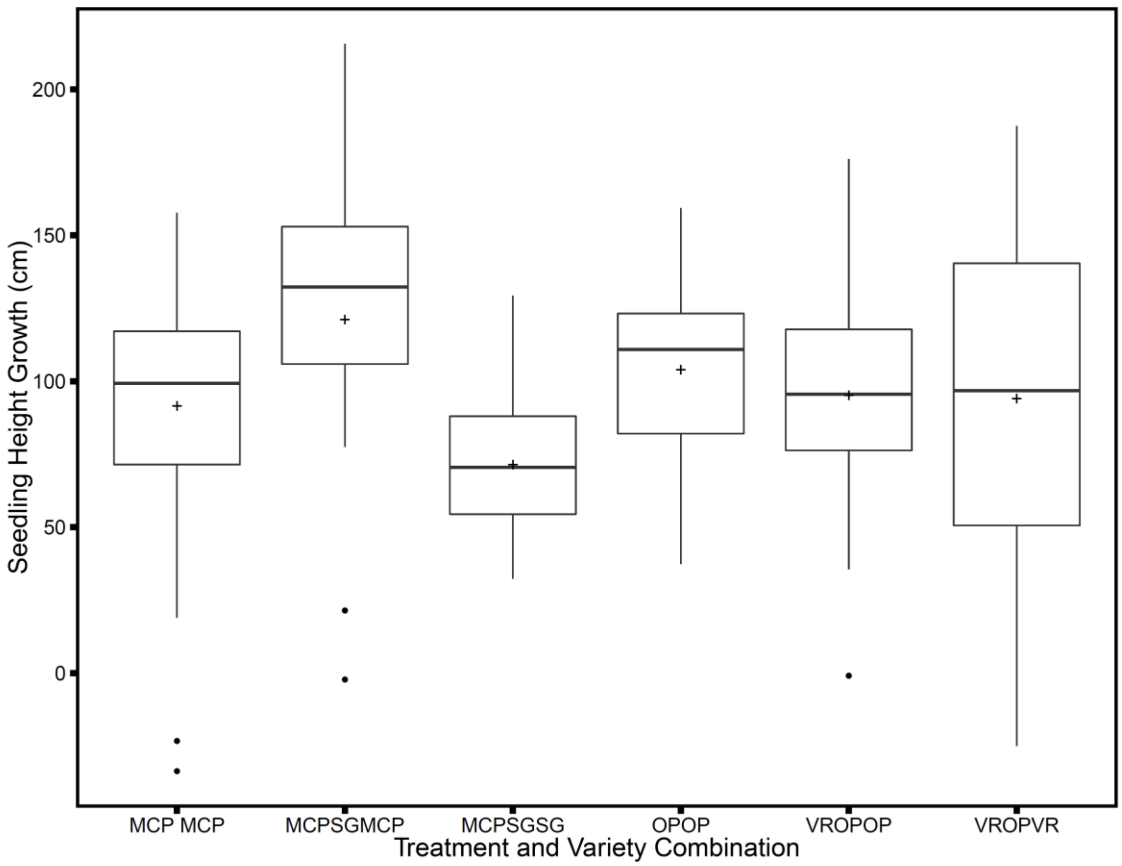

Figure 7. Seedling height growth from the southern tract (first to second growing season) by treatment and variety combination. The box plot shows the mean (+), median (Q_2), 25th percentile (Q_1), and 75th percentile (Q_3) as well as outliers (dots). Outliers are defined as values greater than Q_3+ 1.5 IQR (interquartile range) or less than Q1-1.5IQR.

23.26 mm and standard deviation of 7.61mm (Table 6) (Figure 8). Tukey's HSD comparison of the least square means suggest that there were no significant differences in RCD growth between the OP seedlings in the VROP treatment (M=24.24 mm, SE=5.61 mm), the VR seedlings in the VROP treatment (M=23.09 mm, SE=5.61 mm), the OP seedlings in the control (M=21.96 mm, SE=5.61 mm), the MCP seedlings in monoculture (M=21.90 mm, SE=5.61 mm), the MCP seedlings in the MCPSG treatment (M=18.51 mm, SE=5.61 mm), and the SG seedlings in the MCPSG treatment (M=13.42 mm, SE=5.61 mm).

Discussion

In the north tract, survival was high in all seedlings after the third growing season, with the exception of the SG seedlings. After the fourth growing season, the survival rate of seedlings was still high in the MCP seedlings in monoculture and in the MCPSG treatment, VR seedlings in the VROP treatment, and OP seedlings in monoculture and in the VROP treatment. The survival of sweetgum, however, dropped to 0%. In comparison, in the south tract, the survival rate after the first growing season was high in MCP seedlings in monoculture, VR seedling in the VROP treatment, OP seedlings in the VROP treatment, as well as high in the OP seedlings in monoculture. However, survival was not high in the MCP seedlings in the MCPSG treatment, as well as the SG seedlings in the MCPSG treatment. In after the second growing season, survival was still high in the MCP monoculture, the OP monoculture, and in OP and VR seedlings in the VROP FlexStand™. Additionally, the survival of MCP and SG seedlings in the MCPSG FlexStand™ was at the same low percentages of the originally planted seedling. The overall low rate of survival can be attributed to the changing management plans of the seedling trial. While these seedlings were supposed to serve as an experimental and

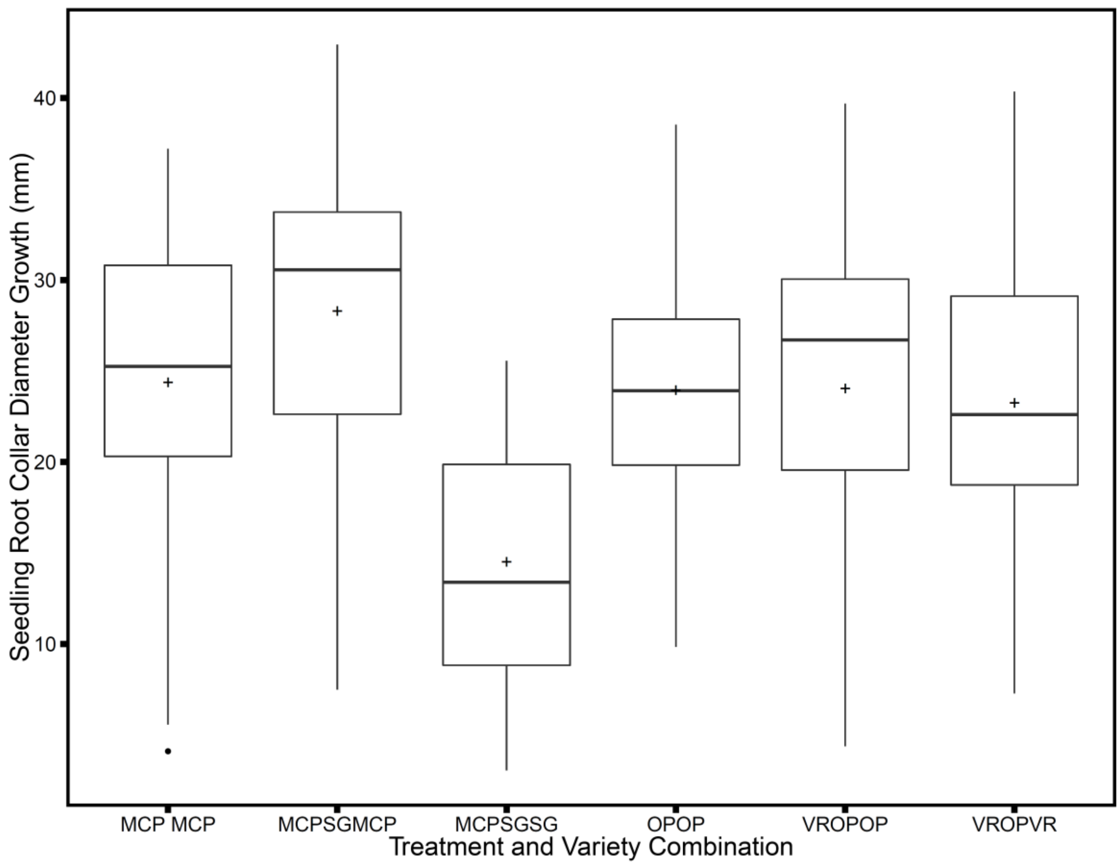

Figure 8. Seedling root collar diameter growth from the southern tract (first to second growing season) by treatment and variety combination. The box plot shows the mean (+), median (Q_2), 25th percentile (Q_1), and 75th percentile (Q_3) as well as outliers (dots). Outliers are defined as values greater than Q_3+ 1.5 IQR (interquartile range) or less than Q1-1.5IQR.

educational trial of ArborGen's genetically improved loblolly pine seedlings, as well as the FlexStand™ silvicultural system, it must also operate as a functional tree farm. According to the narrative of management by Corey Flowers (Flowers Forestry) in Johnson Experimental Forest management plan, herbaceous weed control was very difficult to implement in the treatments containing sweetgum, as the chemicals used to treat herbaceous weeds and unwanted hardwoods would also kill the planted sweetgum. Thus, the decision was made in 2012 to eliminate the sweetgum. A broadcast herbicide was done using 16 ounces of Arsenal AC and spot treat the sweetgum and invading hardwood regeneration using 1oz of Escort NIS. In personal correspondence with Dr. Johnson, it is believed that the broadcast herbicide treatment also led to chemical burns in the non-targeted loblolly pine seedlings. Therefore, while the low survival of sweetgum is not necessarily due competition and seedling quality, it may not be a practical species to plant with loblolly pine due to the complications with chemical release.

In the north tract the height after the first growing season was highest in the MCP seedlings in the MCPSG treatment. In comparison, the MCP seedlings in monoculture were significantly shorter, while the seedlings in the remaining treatments were not different from either. While the findings may suggest that the MCPSG treatment may have some effect on the height after the third growing season of MCP seedlings, this is not the case. In fact, due to difficulties with survival of the MCP seedlings in the monoculture in the first two growing seasons, a fill in planting was done. Therefore, the significant difference in height after the third growing season is likely due to smaller heights of the younger, fill-in seedlings. Additionally, this supports the finding that both OP and VR seedlings in the VROP treatment, and well as the OP seedlings in monoculture are not significantly different from the MCP seedling in monoculture, as the seedlings in the MCP monoculture that survived prior to the fill-in planting may be raising the mean height of the treatment and increasing the standard error. Therefore, it is much more likely that the mean of the MCP monoculture is not significantly different from the MCPSG treatment, but due to the fill-in planting, the sample mean is lower than the population mean of seedlings in MCP monoculture in the third growing season. The differences in mean height between treatments after the fourth growing season changed. MCP seedlings in the MCPSG treatment were still significantly taller than the MCP seedlings in monoculture, but now these MCP seedlings in the MCPSG treatment were also significantly taller than the OP seedlings in the VROP treatment. The sample mean height of the OP seedlings in the VROP treatment may be more representative of the population mean height of OP seedlings in comparison to the sample mean height of the OP seedlings the control due to difficulties differentiating planted OP seedlings from natural regeneration. Thus, the sample mean height of OP seedlings in the control may be higher than the population mean. Therefore, OP seedlings in the control may be significantly shorter than the MCP seedlings in the MCPSG treatment even though the data do not show this. The difference in height from the third to fourth growing season suggest that the MCP seedlings in the MCPSG treatment had a significantly higher rate of growth in comparison the OP seedlings in the VROP treatment, but not in comparison to the other treatments. As the OP seedlings in the VROP treatments may be a more accurate approximation of the population mean growth rate of the OP seedlings due to the complications with natural regeneration in the control plot, the data suggest that the rate of growth may be higher in MCP seedlings than in the OP seedlings.

The Tukey's HSD comparison of least square means of RCD in the north tract after the third growing season suggest that there were no significant differences in RCD between treatments. With the complications of the fill in plantings present in the MCP monoculture, one would expect that the mean RCD of the MCP seedlings in monoculture would follow a similar pattern as the height and be significantly smaller; however the mean RCDs were not significantly different. Similarly, there were no significant differences in the RCD between treatments after the third growing season. In addition, the comparison of RCD growth between treatments found no significant differences between treatments. These findings coincide with research from Paul et al. who found that diameter, as well as height did not differ between clones and full-sibling seedlings of loblolly pine in the first five years after planting (1997).

The mean height in the south tract after the first growing season suggest that the mean height MCP and SG seedlings in the MCPSG treatment as well as the VR seedling in the VROP treatment, while no significantly from each other, were significantly taller that the OP seedlings in the VROP treatment, the OP seedlings in control, as well as the MCP seedlings in monoculture. While these findings may suggest that treatment may have a significant effect on height in the first growing season, there are many confounding factors that may contest this significance. First, one must consider the origin of the seedlings. In this case, all of the seedlings were bareroot cut from the same nursery, however the treatment differences in the seedling types prior to planting are not known. These treatments could include fertilizer, water, and bedding. Loblolly pine, especially genetically improved clones, have been shown to shift carbon allocation in response to fertilizer, which could result in larger RCD and height upon deployment from the nurseries (Stovall et al. 2011). Therefore height growth, as well as RCD growth may be more meaningful measures for this study. After the second growing season, however, there were no significant differences in height between treatments. This finding suggest two possibilities, that 1) the growth rates of the seedlings by genotype and treatment were different, due to external factors within the treatment block or 2) the factors beyond the control of the experiment, such as seedling origin, nursery treatments, initial planting height differed between seedling type. The comparison of vertical growth suggest that the differences in height from the first and second growing seasons suggest that there were no significant differences in vertical growth between treatments from the first growing season to the second growing season. This supports the second possibility that initial height is greatly influenced by seedling origin, nursery treatments, and planting depth. Therefore, initial height may not me as meaningful of a measurement as growth rate for seedlings in the first and second growing seasons.

In the south tract, the VR seedlings in the VROP treatment had significantly larger mean RCD in comparison to the other treatments. For the factors previously mentioned in regards to nursery treatment prior to planting could explain the differences in RCD between the VR seedlings and the other full-sibling (MCP) and half-sibling (OP) seedlings. It also important to consider that RCD may play a critical role in growth, as larger initial diameters may lead to early growth gains (South et al. 2001). Therefore, one may expect the pattern of height growth within the first two growing seasons to coincide with the pattern of initial RCD size and growth, especially if the RCD were significantly different when planted. However, the mean RCD comparisons after the second growing season suggested no significant differences in RCD, which coincides with the pattern of height difference from the first and second growing seasons. Furthermore, the difference in RCD growth between treatments from the first and second growing seasons suggest that there were no significant differences in RCD growth between treatments.

Despite the confounding factors of treatment difference due to an evolving management plan, we can conclude several findings from the seedling trial at the Johnson experimental forest. First, sweetgum may not be a practical biomass plant with Loblolly Pine within the FlexStand™ silvicultural system due to its sensitivity to herbicide for hardwood control. Second, seedling survival was high in all treatments and genetic input. Third, the MCP seedlings, regardless of treatment, did not differ significantly from clonal (VR) seedlings, which coincides with prior research. Finally, while initial and second year height and RCD comparisons may have been significant between genotypes and treatments, the comparisons are not very meaningful, as several uncontrolled factors such as seedling origin, treatment within the nursery, as well as seedling handling. A more meaningful comparison to assess seedling establishment is height growth and RCD growth. Our findings suggest that height and RCD growth in treatments did not differ significantly between clones, full-sibling (MCP), and half-sibling (OP) seedlings in the first and second growing seasons, but did differ significantly between the full-sibling seedlings and half-sibling (OP) seedlings in the third and fourth growing seasons.

CHAPTER III

GROWTH RESPONSES OF GENETICALLY IMPROVED OPEN-POLLENATED AND FULL-SIBLING LOBLOLLY PINE IN THE FLEXSTAND SILVICULTURAL SYSTEM IN THE 9TH YEAR

HYPOTHESES

We hypothesize that the MCP loblolly pine trees will be taller, have larger diameters, and have better growth quality in comparison to open pollinated loblolly pine varieties. Furthermore, we hypothesize that MCP trees will have less incidence of rust, ramicorn branches, and forked stems. We also hypothesize that trees in the FlexStand™ Silvicultural System will produce comparable amounts of sawtimber and pulpwood volume.

OBJECTIVES

The purpose of this study was to: 1) quantify the survival, growth, and quality of full- and half-sibling families after the 9th growing season 2) compare growth characteristics of genetically improved loblolly pine in the ArborGen's FlexStand™ Silvicultural System to varying genetic input, as well as to monocultures.

MATERIALS AND METHODS

Study Site Description

The long term trial of the FlexStand system was planted in January 28, 2003, and located in the Marht Forest in Russel County, Alabama. For the purposes of this study, the current stand was measured, in its 9th growing season. The previous stand site index was 58' at 25 years. Site preparations included a chemical site prep using 16 oz/ac Chopper and 5 qts/ac Accord in June of 2001, and a mechanical preparation of bedding using a savannah plow in September of 2002.

Competition control was done using 0.5oz/ac Oust and 10 oz/ ac Oustar in 6 foot bands in the spring of the first and second growing seasons (2003 and 2004, respectively). The seedlings were obtained from the ArborGen nursery in Ravenel, South Carolina.

Experimental Design

The Marht forest experimental design was a randomized complete block and consisted of three replicates (blocks) of five genetic combinations (treatments). Three treatments consisted of monocultures of open pollinated (AL) trees, half-sibling trees (WV3), and mass control pollinated (full-sibling, MCP) trees planted at a 14' x 6' spacing. The two additional treatments consisted of ArborGen's FlexStand™ silvicultural system, using MCP trees planted in a 14' x 7' spacing with every third row consisting of AL or WV3, at a 14' x 5' spacing. The following seven genetic input and treatment combinations for comparison resulted: AL trees in monoculture (ALAL), WV3 trees in monoculture (WV3WV3), MCP trees in monoculture (MCPMCP), MCP trees in the MCP/AL FlexStand™ (MCP/ALMCP), MCP trees in the MCP/WV3 FlexStand™ (MCP/WV3MCP), WV3 trees in the MCP/WV3 FlexStand™ (MCP/WV3WV3), and AL trees in the MCP/AL FlexStand™ (MCP/ALAL). The replicates were blocked along an elevation gradient, where each block was aligned along a line of equal elevation (Figure 9).

Each treatment plot was approximately 2 acres with a single quarter acre sample plot. Several quantitative and qualitative measurements of growth responses taken, including diameter at breast height (DBH), height-to-live crown, total height, stem quality (rated on 0-5 scale, with 5 indicating pole trees), as well as presence/absence data for tree mortality, forked stems, ramicorn branching, and fusiform rust. Hegyi's index was calculated to assess competition using a minimum neighborhood of 19.8 m in FlexStands and 18.44 m in monocultures (1974). Van Duesen et al.'s combined variable equation for volume of loblolly pine

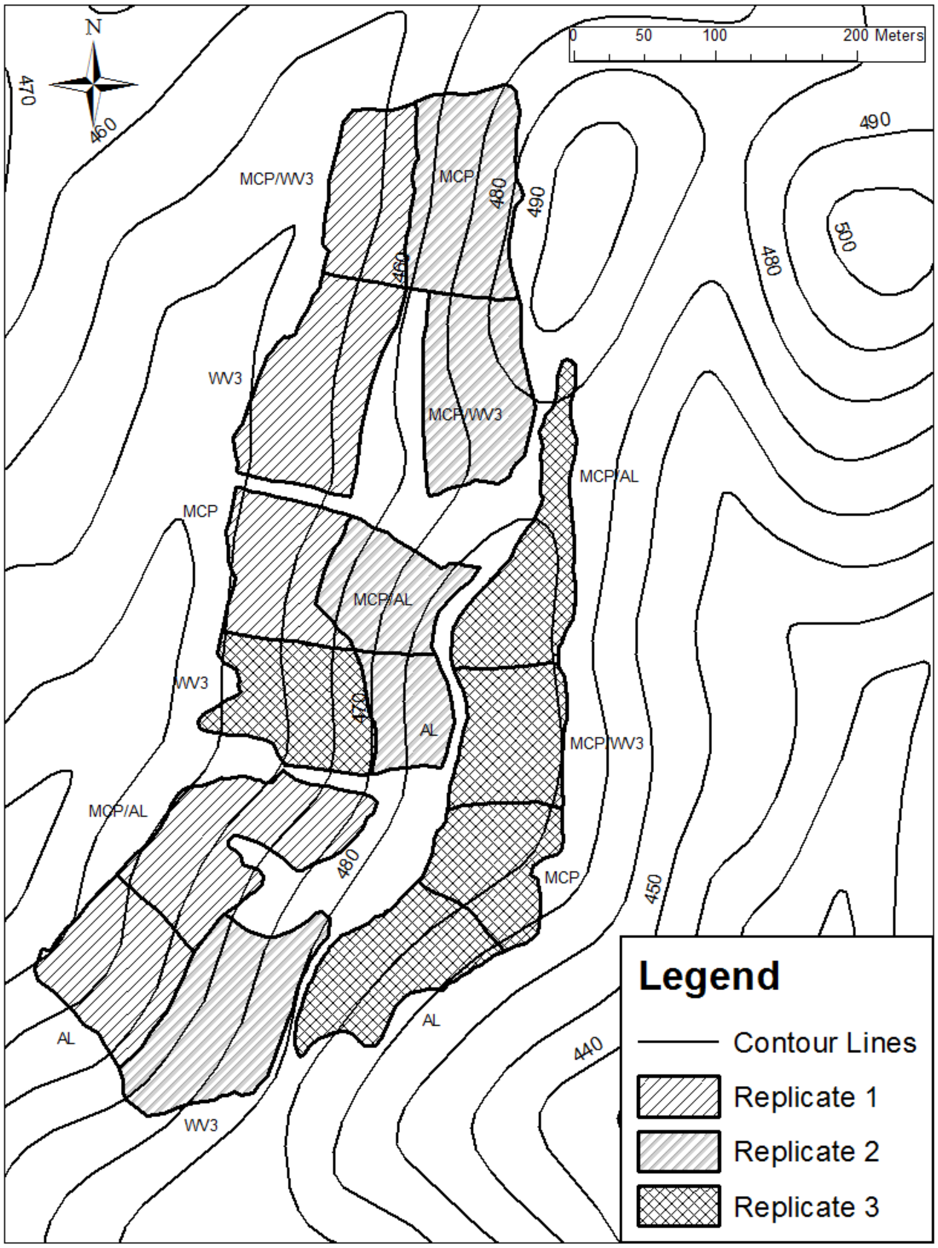

Figure 9. Topographical map of study site stands in Marht forest, Hatchechubbee, Alabama. Arrangement of monoculture (AL, MCP, WV3) and FlexStand™ replicates shown.

was used to estimate wood volume using DBH and total height (1981). Mean stand volume and basal area were calculated across genotype and treatments. Furthermore, the mean stand volume first and fourth rows, as well as the second, third, fifth, and sixth rows of MCP monocultures were calculated separately to compare mean stand volumes to biomass and sawtimber rows of FlexStands™, respectively. Volume to weight conversion were done using Mississippi State Extension Service's conversion factor of 2.6 tons per cord (Dicke and Parker 2010). Pulpwood and sawtimber prices were calculated using current market values listed for southern yellow pine available through Timber Mart-South.

Statistical Analysis

The randomized complete block design was analyzed with a General Linear Model (GLM) procedure on JMP (JMP®, Version *10*. SAS Institute Inc., Cary, NC, 1989-2007). The least square mean (LS mean) of each growth and quality measurement was taken for each plot and genotype. The LS mean for each sample plot was treated as a single observation. A series of LS mean contrasts (Table 7) was used to assess the effects of treatment, genotype, and treatment *genotype effects on each measured and calculated growth characteristic. Chi-square analysis was used to assess differences in tree quality. Plots were created in R version 3.0.1 ggplot2 package (Wickham 2009, R Core Team 2014). Maps were created using ESRI ArcMap 10.1 (2011).

Table 7. Least square mean contrasts. The genotype being contrasted is shown outside parentheses while the treatment is shown within parenthesis.

Genotype(Treatment) Contrasts	
Genotype Contrasts Monoculture	
+	**-**
MCP(MCP)	**AL(AL)**
MCP(MCP)	**WV3(WV3)**
AL(AL)	**WV3(WV3)**
Genotype(Treatment) Contrasts FlexStand	
+	**-**
MCP(MCP/AL)	**MCP (MCP/WV3)**
MCP(MCP/AL)	**MCP (MCP)**
MCP (MCP/WV3)	**MCP (MCP)**
AL(MCP/AL)	**AL(AL)**
MCP(MCP/WV3)	**WV3(WV3)**

RESULTS

Growth Responses of Loblolly Pine Monocultures

AL monocultures had a mean survival rate of 0.854 with a standard error of 0.0247. WV3 trees had a mean survival rate of 0.907 and a standard error of 0.0247. MCP trees had a mean survival rate of 0.917 and a standard error of 0.0247. The contrast of least square means suggest that the mean survival rate of MCP trees was not significantly higher than the mean survival rate of AL trees (F-ratio (1, 12) = 3.2183 p=0.0980) or WV3 trees (F-ratio (1, 12) =0.0810, p=0.7808). The mean survival rate of WV3 trees was also not significantly different from the mean survival rate of AL trees (F-ratio (1, 12) =2.2782, p=0.1571) (Figure 10).

The DBH of AL trees ranged from 4.9 cm to 23.9 cm, with a least square mean of 14.71 cm with and a standard error of 0.35 cm. WV3 trees had a DBH that ranged from 5.7 cm to 22 cm, with a least square mean of 15.01 cm and a standard error of 0.35 cm. MCP trees had a DBH that ranged from 5.2 cm to 21.7 cm, with a least square mean of 15.27 cm and standard error of 0.35 cm. The least square mean contrasts suggest that the mean DBH of MCP trees was not significantly higher than the mean DBH of AL trees (F-ratio (1, 12) = 1.1934, p=0.2961). The mean DBH of MCP trees was also not significantly higher than the mean DBH of WV3 trees (F-ratio (1, 12) = 0.2630 p=0.6173). The mean DBH of WV3 trees was not significantly different from the mean DBH of AL trees (F-ratio (1, 12) =0.3359, p=0.5729) (Figure 11).

The height-to-live-crown of AL trees ranged from 2.4 m to 14.4 m, with a least square mean of 5.40 m and standard error of 0.23 m. WV3 trees had a height-to-live-crown that ranged from 2.4 m to 16.9 m with a least square mean of 5.48 m and standard error of 0.23 m. MCP

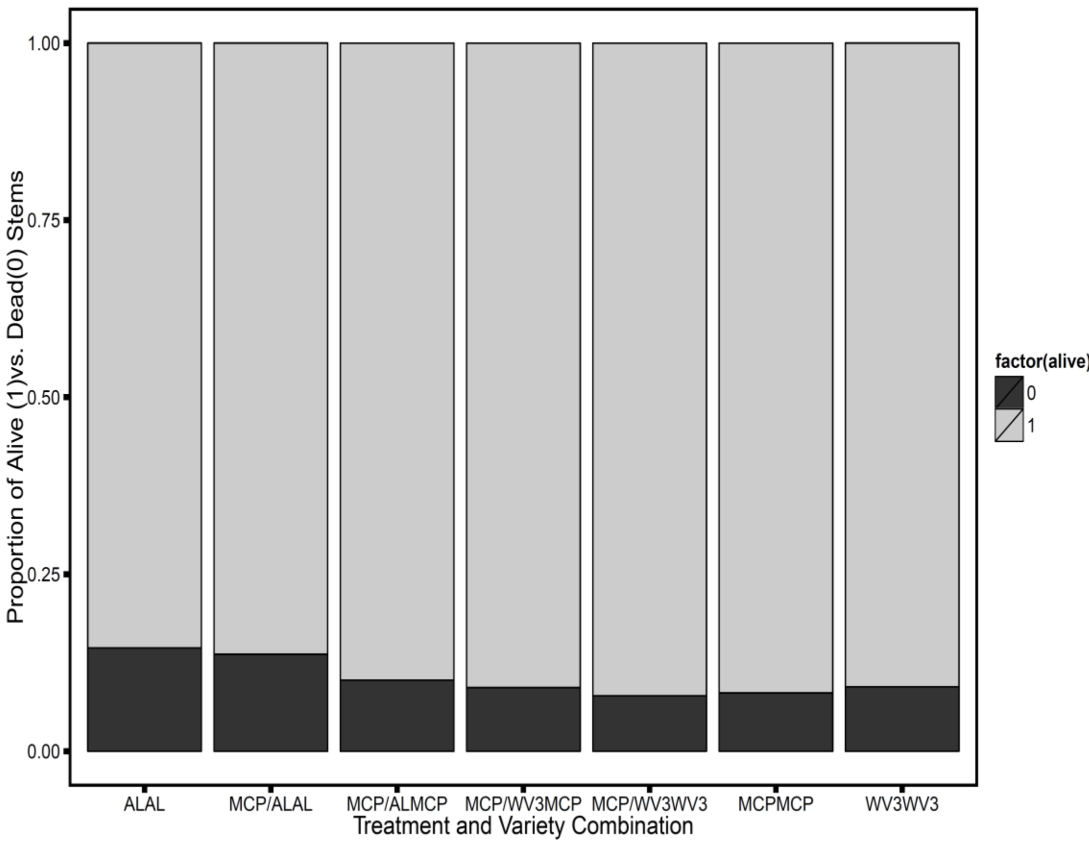

Figure 10. Proportion of alive stems (light grey bars) and dead stems (black bars) distributed between separate treatments (MCP, WV3, and AL monocultures vs. MCP/AL, and MCP/WV3 FlexStands™) and each tree variety (MCP, WV3, and AL) within each FlexStand™.

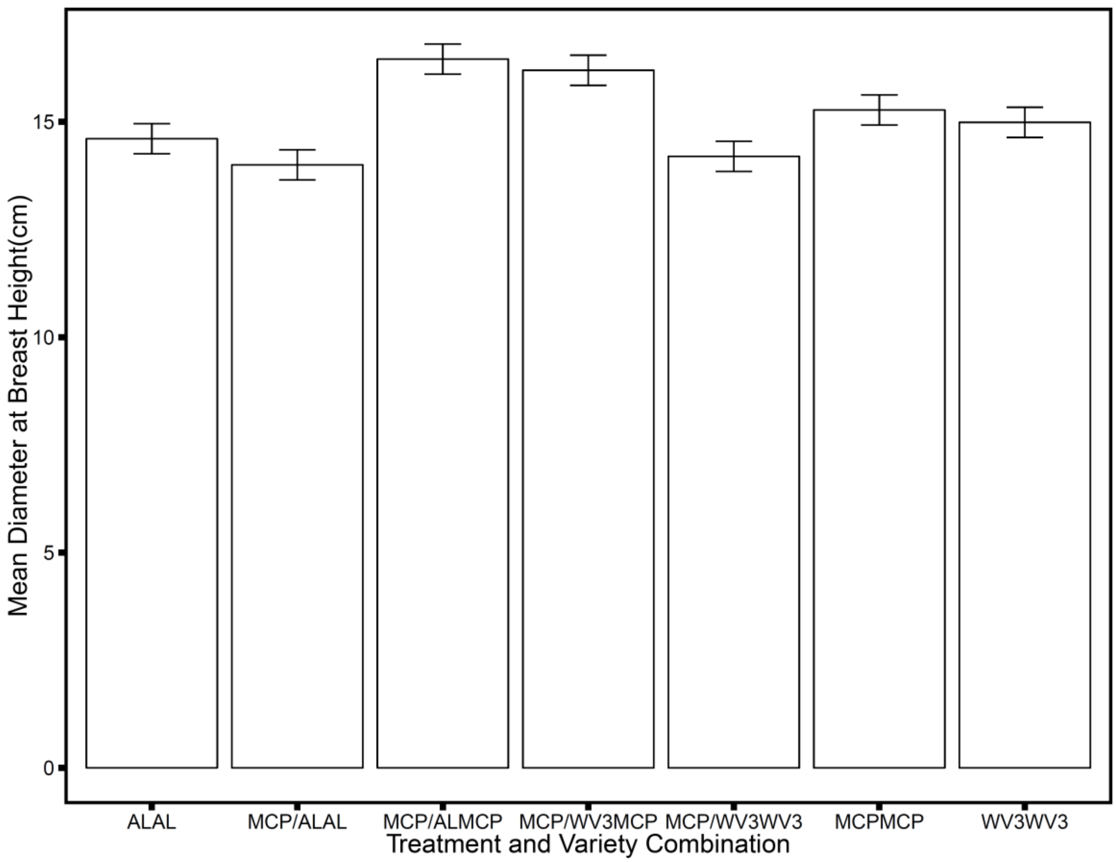

Figure 11. Diameter at breast height (DBH) distributed between separate treatments (MCP, WV3, and AL monocultures vs. MCP/AL, and MCP/WV3 FlexStands™) and each tree variety (MCP, WV3, and AL) within each FlexStand™. Box plots are shown with means displayed as addition symbols.

trees had a height-to-live-crown that ranged from 3.2 m to 8.2m with a least square mean of 5.78 m and standard error of 0.23 m. The least square mean contrast suggest that the mean height-to-live-crown of MCP trees was not significantly higher than that of AL trees (F-ratio (1, 12) =1.3169, p=0.2735). The mean height-to-live-crown of MCP trees was also not significantly higher than that of WV3 trees (F-ratio (1, 12) = 0.8447, p-value= 0.3762). The mean height-to-live-crown of WV3 trees was not significantly different from the mean height-to-live-crown of AL trees (F-ratio (1, 12) =0.0522, p=0.8231) (Figure 12).

The total height of AL trees ranged from 3.7 m to 15.1 m with a least square mean of 11.4 m and standard error of 0.39 m. The total height of WV3 trees ranged from 5.3 m to 16.6 m with a least square mean of 12.47 m with a standard error of 0.39 m. The total height of MCP trees ranged from 6.9 m to 16.7 m with a least square mean of 13.23 m and standard error of 0.39 m. The least square mean contrasts suggest that MCP trees were significantly taller than AL trees (F-ratio (1, 12) =10.9544, p=0.0062). The mean total height of MCP trees, however, was not significantly taller than the mean total height of WV3 trees (F-ratio (1, 12)= 1.8974, p=0.1935). The mean total height of WV3 trees was not significantly different from the mean total height of AL trees (F-ratio (1, 12) =3.7337, p=0.0773) (Figure 13).

The mean presence of fusiform rust infection in AL trees was 0.135 with a standard error of 0.038. The mean presence of fusiform rust in WV3 trees was 0.130 with a standard error of 0.038. The mean presence of fusiform rust in MCP trees was 0.058 with a standard error of 0.038. The least square mean contrasts suggest that the mean presence of fusiform rust in MCP trees was not significantly lower than in AL trees (F-ratio (1, 12) =2.0093, p=0.1818). The mean presence of fusiform rust in MCP trees was also not significantly lower than in WV3 trees

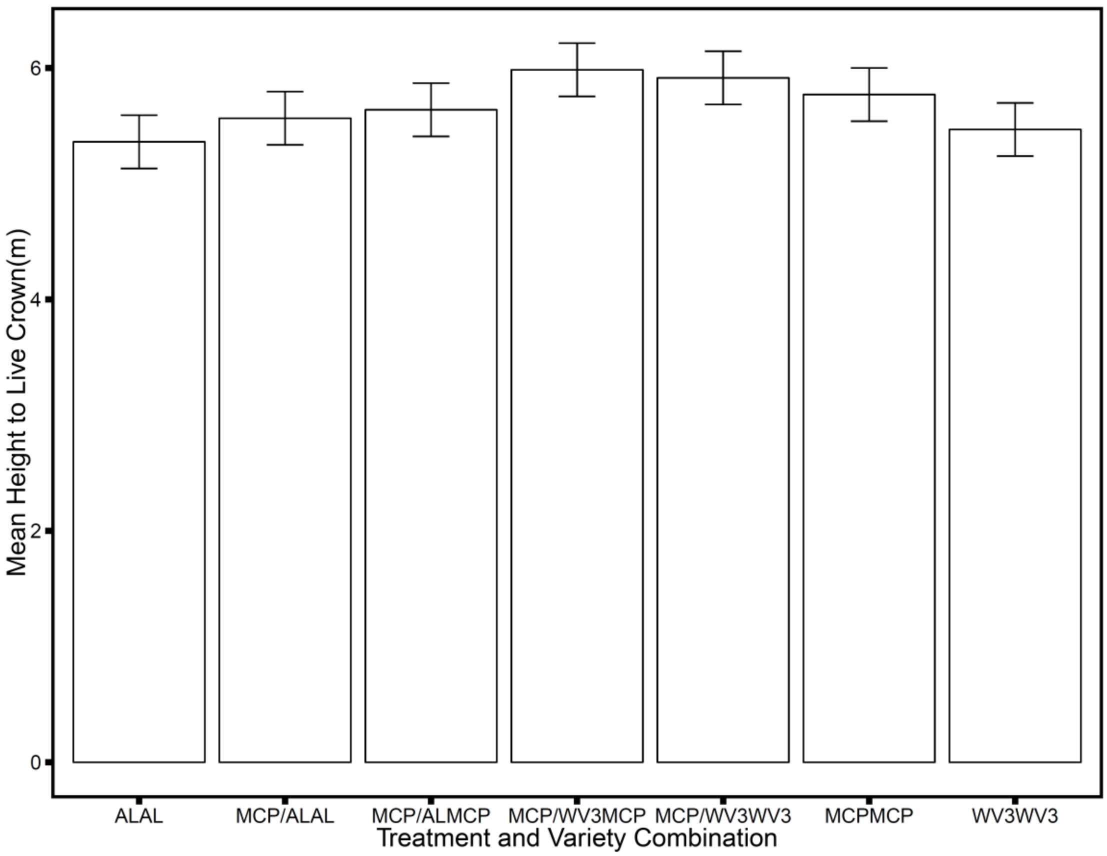

Figure 12. Height-to-live-crown distributed between separate treatments (MCP, WV3, and AL monocultures vs. MCP/AL, and MCP/WV3 FlexStands™) and each tree variety (MCP, WV3, and AL) within each FlexStand™. Box plots are shown with means displayed as addition symbols.

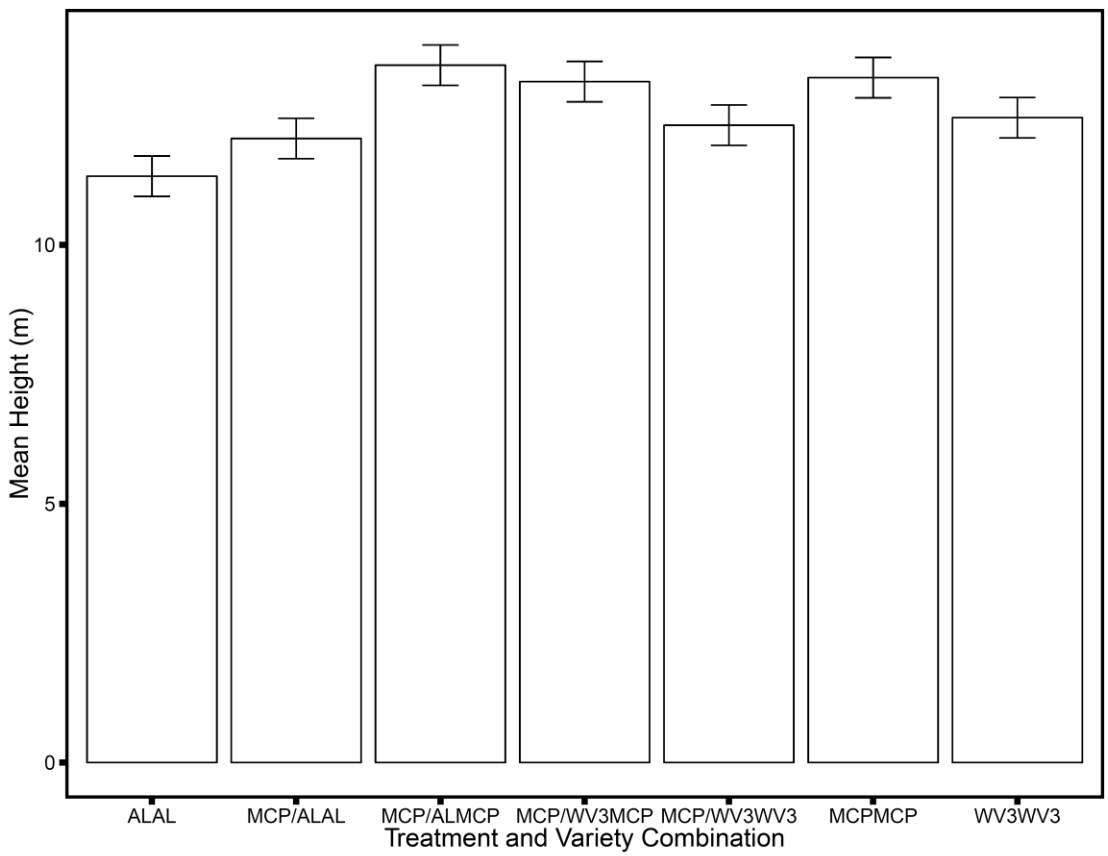

Figure 13. Total height distributed between separate treatments (MCP, WV3, and AL monocultures vs. MCP/AL, and MCP/WV3 FlexStands™) and each tree variety (MCP, WV3, and AL) within each FlexStand™.

(F-ratio (1, 12) =1.7817, p=0.2067). Additionally, the mean presence of fusiform rust in WV3 was not significantly different from that of AL trees (F-ratio (1,12)=0.0068, p=0.9355) (Figure 14).

The mean presence of ramicorn branching in AL trees was 0.473 with a standard error of 0.0526. The mean presence of ramicorn branching in WV3 trees was 0.414 with a standard error of 0.0526. The mean presence of ramicorn branching in MCP trees was 0.192 with a standard error of 0.0526. The least square mean contrasts suggest that MCP trees had significantly less ramicorn branching than AL trees (F-ratio (1, 12) =14.3048, p=0.0026). MCP trees also had significantly less ramicorn branching than WV3 trees (F-ratio (1, 12) =8.932, p=0.0113). WV3 trees, however, did not show any significant difference in ramicorn branching in contrast to AL trees (F-ratio (1, 12) =0.6291, p=0.4429) (Figure 15).

The mean presence of forking in AL trees was 0.128 with a standard error of 0.022. The mean presence of forking in WV3 trees was 0.099 with a standard error of 0.022. The mean presence of forking in MCP trees was 0.038 with a standard error of 0.022. The least square mean contrast results suggest that the mean presence of forking in MCP trees was significantly lower than the mean presence of forking in AL trees (F-ratio (1, 12) =8.1581, p=0.0145). The mean presence of forking in MCP trees was not significantly different than the mean presence of forking in WV3 trees F-ratio (1, 12) =3.7254, p=0.0776). Additionally, the mean presence of forking in WV3 trees was not significantly different from the mean presence of forking in AL trees (F-ratio (1, 12) =0.8577, p=0.3726) (Figure 16).

The mean quality value of AL trees was 2.49 with a standard error of 0.17. The mean quality value of WV3 trees was 2.58 with a standard error of 0.17. The mean quality value of MCP trees was 3.08 with a standard error of 0.17. The least square mean contrast results suggest that MCP trees had a significantly higher mean quality value than AL trees (F-ratio (1,

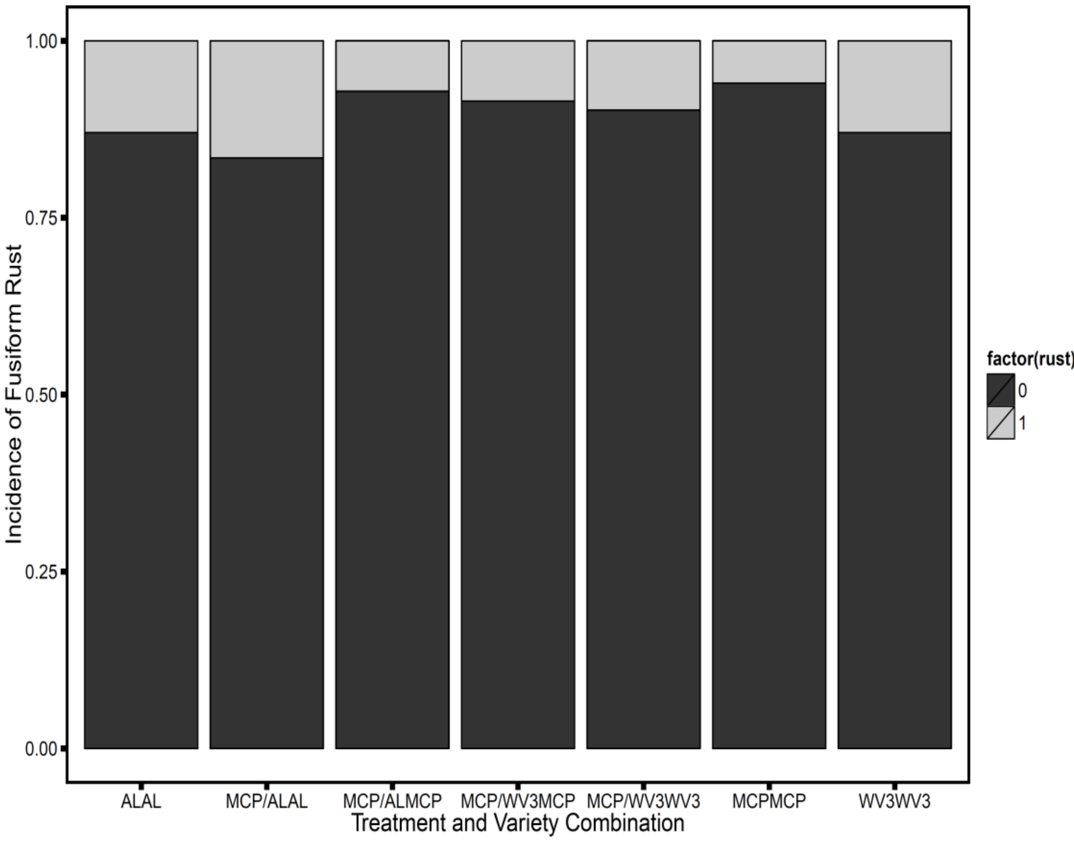

Figure 14. Incidence of fusiform rust distributed between separate treatments (MCP, WV3, and AL monocultures vs. MCP/AL, and MCP/WV3 FlexStands™) and each tree variety (MCP, WV3, and AL) within each FlexStand™. Percentage of infection is indicated by the light grey bar while percentage of non-infection is indicated by the black bars.

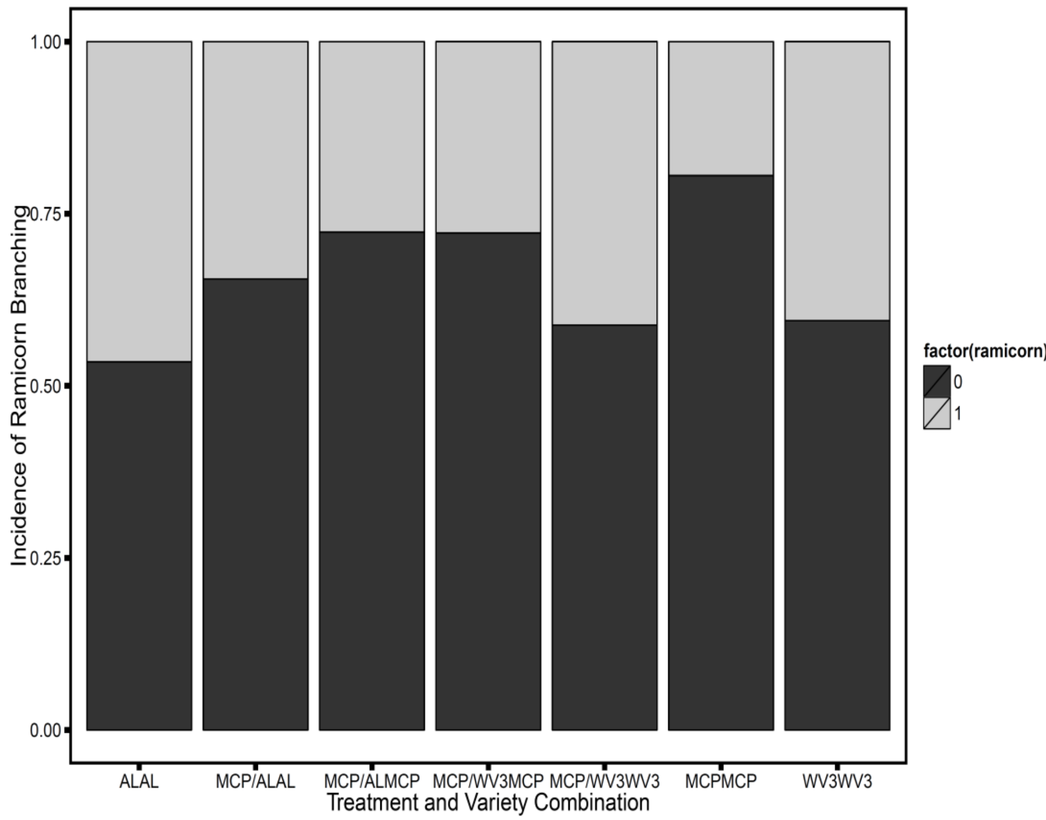

Figure 15. Incidence of ramicorn branches distributed between separate treatments (MCP, WV3, and AL monocultures vs. MCP/AL, and MCP/WV3 FlexStands™) and each tree variety (MCP, WV3, and AL) within each FlexStand™. Percentage of trees with ramicorn branches is indicated by the light grey bar while the percentage of trees without ramicorn branches is indicated by the black bars.

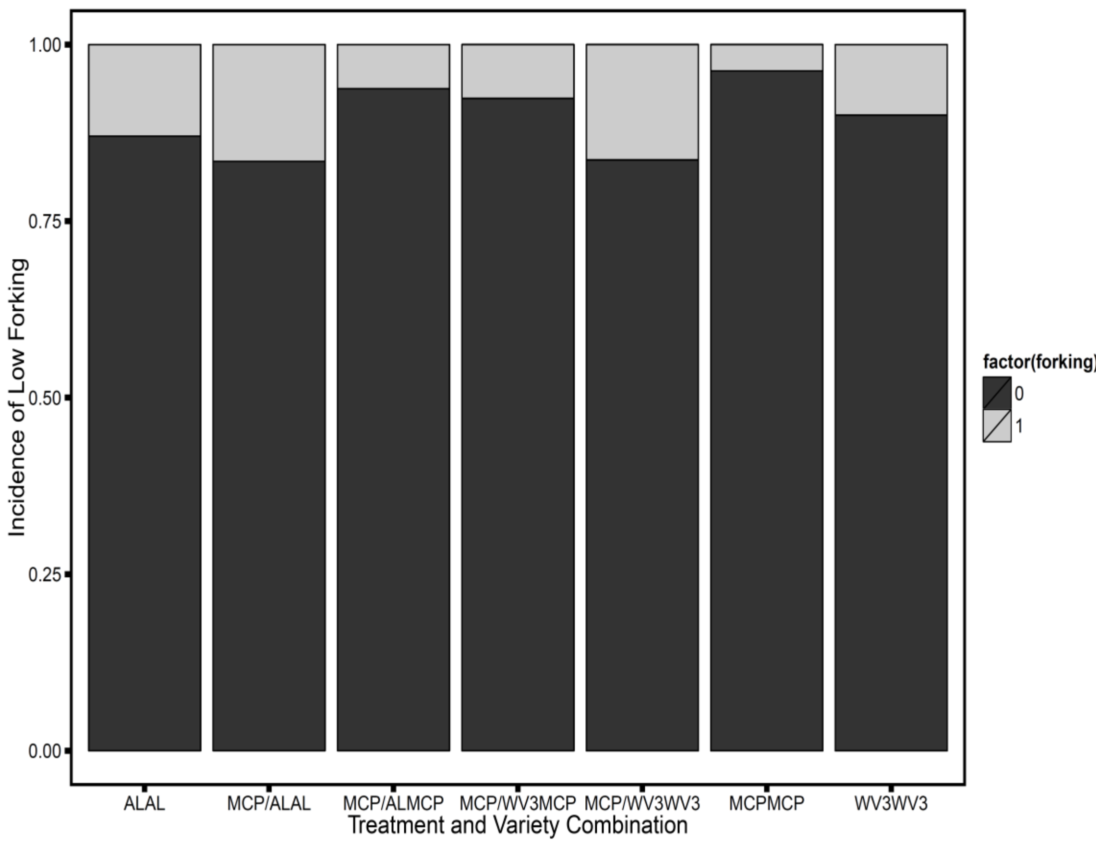

Figure 16. Incidence of forked stems distributed between separate treatments (MCP, WV3, and AL monocultures vs. MCP/AL, and MCP/WV3 FlexStands™) and each tree variety (MCP, WV3, and AL) within each FlexStand™. Percentage of trees with forked stems is indicated by the light grey bar while the percentage of trees without forked stems is indicated by the black bars.

12) = 5.6653, p=0.0348). However, MCP trees did not have a significantly different mean quality value than WV3 trees (F-ratio (1, 12) = 4.0738, p=0.0665). Additionally, the mean quality value of WV3 trees was not significantly different from the mean quality value of AL trees (F-ratio (1, 12) = 0.1309, p=0.7238). When analyzed with a contingency table, 0% was rated as 0, 11.04% of AL trees were rated as 1, 32.49% were rated as 2, 52.37% were rated as 3, 4.10% were rated as 4, and 0% was rated as 5. For WV3 trees, 0% was rated as 0, 10% were rated as 1, 32.70% were rated as 2, 47.57% were rated as 3, 9.73% were rated as 4, and 0% was rated at 5. For MCP trees, 0% was rated at 0, 5.49% were rated at 1, 44.64% were rated at 3, 25.69% were rated at 4, and 5.99 were rated at 5 (Figure 17). A Chi Square analysis of monocultures suggest that there were non-random distributions of tree quality values by genotype and treatment (χ^2=146.103, p<0.0001).

The volume of AL trees ranged from 0.0011 to 0.0848 cords per tree with a least square mean of 0.0268 cords per tree and a standard error of 0.0019 cords. The volume of WV3 trees ranged from 0.00273 to 0.0682 cords per tree with a least square mean of 0.0301 cords per tree and standard error of 0.0019 cords. The volume of MCP trees ranged from 0.0028 to 0.0774 cords per tree with a least square mean of 0.0327 cords per tree and standard error of 0.0019 cords. The least square mean contrast results suggest that MCP trees had a comparatively higher per tree volume of wood when compared to AL trees, albeit marginally not significant (F-ratio (1,12) = 4.6093, p=0.0529). In comparison, the mean volume of wood per tree of MCP trees was not significantly different from that of WV3 trees (F-ratio (1,12)= 0.9097, p=0.3590) (Figure 18).

The least square mean stand volume of AL monocultures was 11.422 cords per acre, with a standard error of 0.8381 cords per acre. The least square mean stand volume of WV3

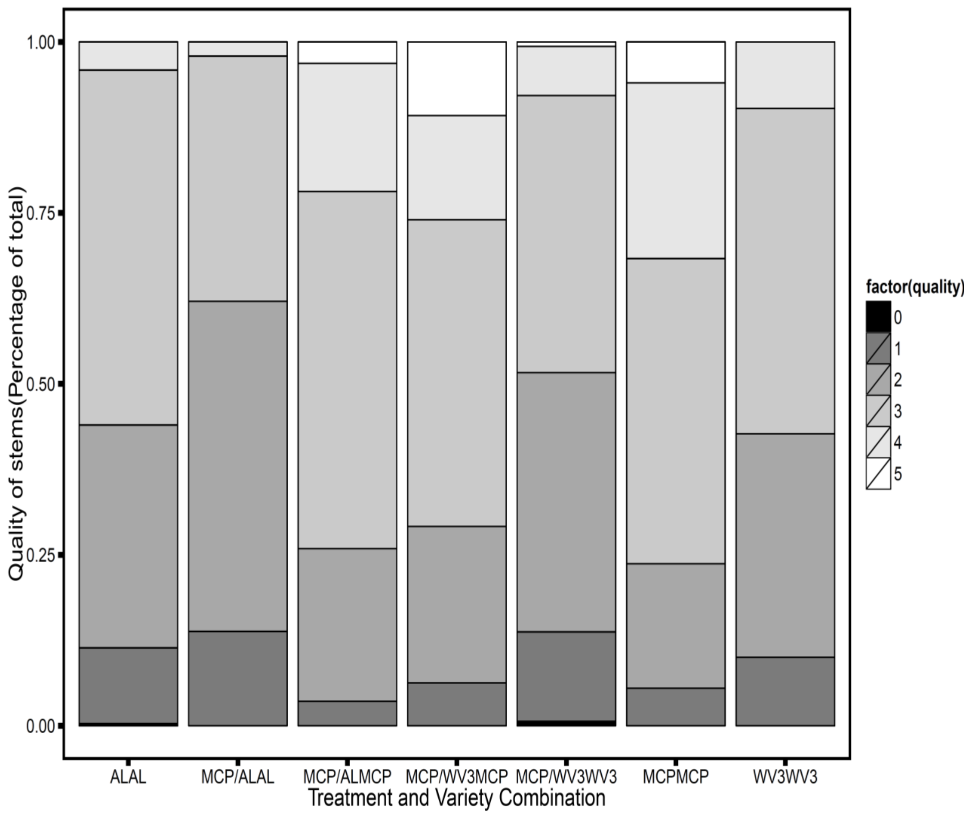

Figure 17. Percent distribution of stem quality separated by treatments (MCP, WV3, and AL monocultures vs. MCP/AL, and MCP/WV3 FlexStands™) and each tree variety (MCP, WV3, and AL) within each FlexStand™. Quality is shown as 6 discrete timber quality ratings, 0 (black, lowest rating) to 6 (white, highest rating).

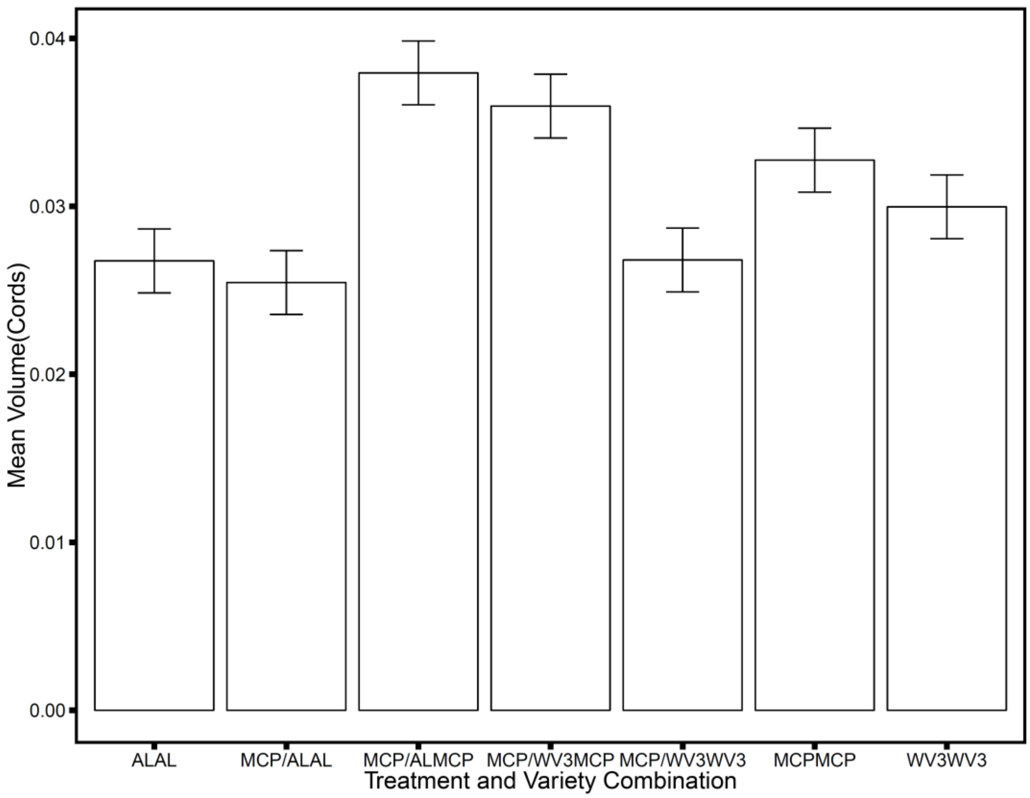

Figure 18. Tree volume distributed between separate treatments (MCP, WV3, and AL monocultures vs. MCP/AL, and MCP/WV3 FlexStands™) and each tree variety (MCP, WV3, and AL) within each FlexStand™. Box plots are shown with means displayed as addition symbols.

monocultures was 14.7858 cords per acre, with a standard error of 0.8381 cords per acre. The least square mean stand volume of MCP monocultures was 17.5095 cords per acre, with a standard error of 0.8381 cords per acre. The least square mean contrast results suggest that MCP monocultures had a significantly higher stand volume when compared to AL monocultures (F-ratio (1,16)=26.3768, p<0.0001). In addition, the least square mean contrast results suggest that the MCP monocultures had a significantly higher stand volume in comparison to WV3 monocultures (F-ratio (1,16)=5.2812, p=0.0354). Furthermore, the least square mean contrast results suggest that the WV3 monocultures had a significantly higher stand volume in comparison to AL monocultures (F-ratio (1,16)=8.0528, p=0.0119) (Figure 19).

The least square mean of stand basal area in AL monocultures was 80.51 square feet per acre, with a standard error of 5.85 square feet per acre. The least square mean of stand basal area WV3 monocultures was 97.15 square feet per acre, with a standard error of 5.85 square feet per acre. The least square mean of stand basal area in MCP monocultures was 108.87 square feet per acre, with a standard error of 5.85 square feet per acre. The least square mean contrast results suggest that the stand basal area of MCP monocultures was significantly higher than that of AL monocultures (F-ratio (1,8) = 11.7303, p=0.009). The least square mean contrast results also suggest that the stand basal area of MCP monocultures was not significantly different from the stand basal are of WV3 monocultures (F-ratio (1, 8) = 2.0035, p=0.1947). Furthermore, the least square mean contrast result suggest that the stand basal area of WV3 monocultures was not significantly different from AL monocultures (F-ratio (1, 8) = 4.0380, p=0.0793) (Figure 20).

In monocultures, competition indices in AL stands ranged from 1.246 to 12.3739, with a least square mean of 3.567 and standard deviation of 0.219. Competition indices in

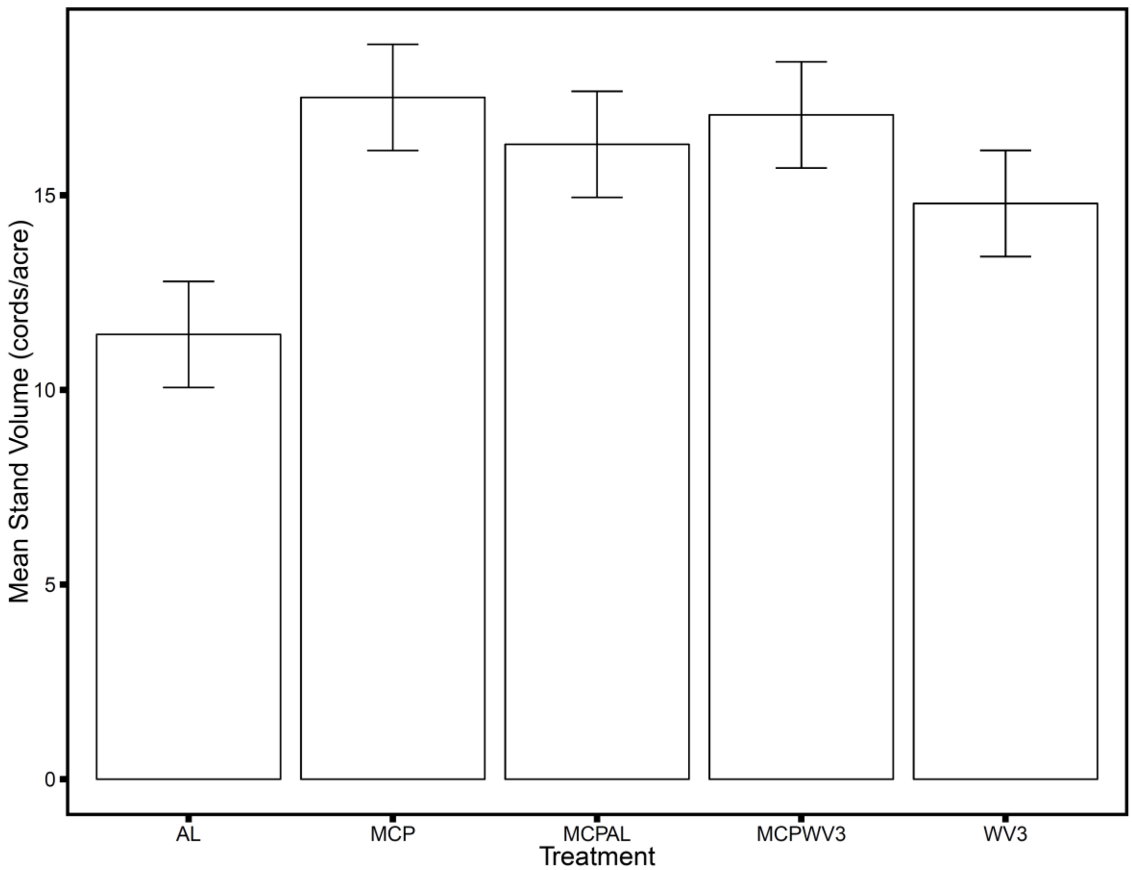

Figure 19. Mean stand volume (cords per acre) by treatment. MCP, WV3, and AL monocultures and MCP/AL, and MCP/WV3 FlexStands™). Standard error of each mean shown.

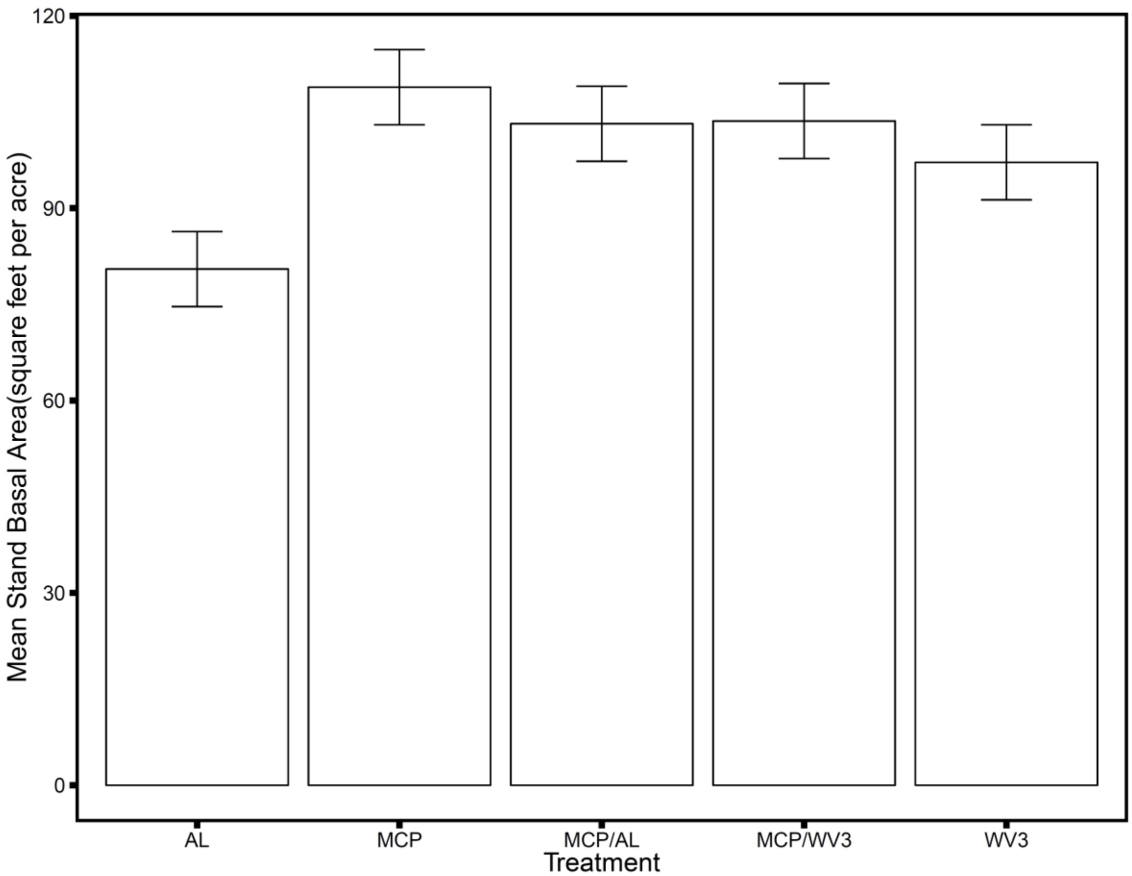

Figure 20. Mean stand basal area (square feet per acre) by treatment (MCP, WV3, and AL monocultures and MCP/AL, and MCP/WV3 FlexStands™). Standard error of each treatment mean shown.

WV3 stands ranged from 1.512 to 10.432, with a least square mean of 3.749 and standard deviation of 1.170. Competition indices in MCP stands ranged from 1.892 to 8.716, with a least square mean of 3.859 and a standard deviation of 0.959. The least square mean contrast results suggest that mean competition index of MCP trees was not significantly different from AL trees (F-ratio (1,14)= 0.8826, p= 0.3634). Additionally, the mean competition index was not significantly different from the mean competition index of WV3 trees (F-ratio (1, 14) = 0.1254, p = 0.7285). The mean competition index of AL trees was not significantly different from the mean competition index of WV3 trees (F-ratio (1, 14) = 0.3426, p=0.5676) (Figure 21).

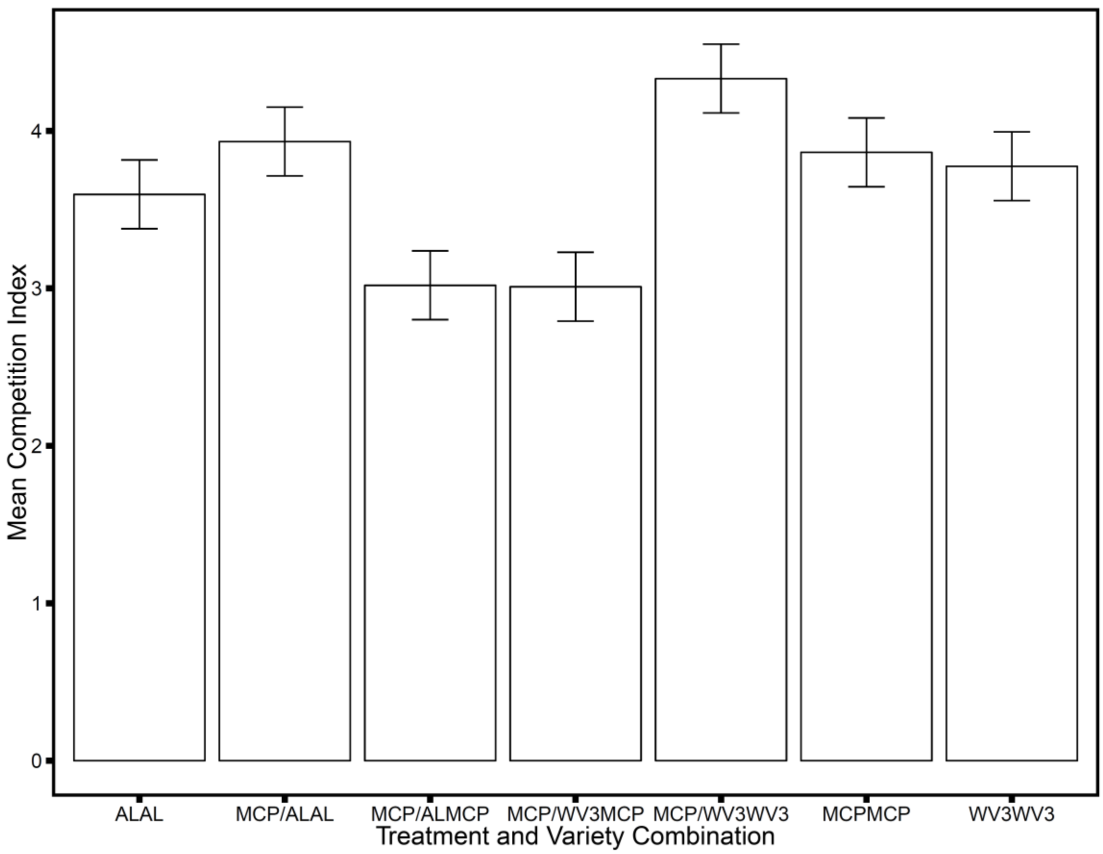

Figure 21. Competition indices of trees distributed between separate treatments (MCP, WV3, and AL monocultures vs. MCP/AL, and MCP/WV3 FlexStands™) and each tree variety (MCP, WV3, and AL) within each FlexStand™. Box plots are shown with means displayed as addition symbols.

Growth Responses of Loblolly Pine in the FlexStand Silviculture System

The MCP trees in MCP/WV3 stands had a mean survival of 0.95 with a standard error of 0.024. The MCP trees in MCP/AL stands had a mean survival of 0.90 with a standard error of 0.024. The least square mean contrast results suggest that the mean survival of MCP trees in the MCP/WV3 stands was not significantly different from the mean survival of the MCP trees in the MCP/AL stands (F-ratio(1,12)=2.0784. p=0.1750). The mean survival of MCP trees in the MCP/WV3 stands was not significantly different from the mean survival of MCP trees in monoculture (F-ratio(1,12)=0.8991, p=0.3617). Additionally, the mean survival of MCP trees in MCP/AL stands was not significantly different from the mean survival of MCP trees in monoculture (F-ratio(1,12)=0.2435, p=0.6306)(Figure 10).

The MCP trees in the MCP/WV3 stands had a DBH that ranged from 6.2 cm to 21.9 cm with a least square mean of 16.20 cm and a standard error of 0.35 cm. The MCP trees in the MCP/AL stands had a DBH that ranged from 5.5 cm to 22.2 cm with a least square mean of 16.46 cm and standard error of 0.35 cm. The least square mean contrast results suggest that the mean DBH of the MCP trees in the MCP/WV3 stands was not significantly different from the mean DBH of MCP trees in MCP/AL stands (F-ratio (1,12)=0.2597, p=0.6196). Additionally, the mean DBH of MCP trees in the MCP/WV3 stands were not significantly different from MCP trees in monoculture (F-ratio(1,12)=3.4937, p=0.0862). However, the mean DBH of MCP trees in the MCP/AL stands was significantly higher than the mean DBH of MCP trees in monoculture (F-ratio(1,12)=5.6582, p=0.0348) (Figure 11).

The MCP trees in MCP/WV3 stands had a height-to-live-crown that ranged from 3.1 m to 8.3 m with a least square mean of 5.97 m and standard error of 0.23m. The MCP trees in MCP/AL stands had a height-to-live-crown that ranged from 2.2 m to 8.4 m with a least square mean of 5.63 m and standard error of 0.23m. The least square mean contrast results suggest that the mean height-to-live-crown of MCP trees in MCP/WV3 stands is not significantly different from MCP trees in the MCP/AL stands (F-ratio (1, 12) =1.0540, p=0.3248). The mean height-to-live-crown of MCP trees in MCP/WV3 stands was not significantly different from the mean height-to-live-crown of MCP trees in monoculture (F-ratio (1, 12) =0.3371, p=0.5723). Additionally, the mean height-to-live-crown of MCP trees in MCP/AL stands was not significantly different from the mean height-to-live-crown of MCP trees in monoculture (F-ratio (1, 12) =0.1990, p=0.6635) (Figure 12).

The mean total height of MCP trees in MCP/WV3 stands ranged from 8.7 m to 15.9 m, with a least square mean of 13.14m and standard error of 0.39m. The total height of MCP trees in the MCP/AL stands ranged from 6.9 m to 16.8 m, with a least square mean of 13.46m and standard error of 0.39m. The results from the least square mean contrast suggest that the mean total height of MCP trees in MCP/WV3 stands was not significantly different from the mean total height of MCP trees in MCP/AL stands (F-ratio (1, 12) =0.3306, p=0.5759). The mean total height of MCP trees in MCP/WV3 stands was not significantly different from the mean total height of MCP trees in monoculture (F-ratio (1, 12) =0.0259, p=0.8747). Additionally, the mean total height of MCP trees in MCP/AL stands was not significantly different from the mean total height of MCP trees in monoculture (F-ratio (1, 12) = 0.1713, p=0.6863) (Figure 13).

The mean presence of rust in MCP trees in MCP/WV3 stands was 0.087 with a standard error of 0.038. The mean presence of rust in MCP trees in MCP/AL stands was 0.072 with a standard error of 0.038. The results from the least square mean contrasts suggest that the mean presence of rust in MCP trees in MCP/WV3 stands was not significantly different from the mean presence of rust in MCP trees in MCP/AL stands (F-ratio (1, 12)=0.0790, p=0.7834). The mean presence of rust in MCP trees in MCP/WV3 stands was not significantly different from the mean presence of rust in MCP trees in monoculture (F-ratio (1, 12) =0.2856, p=0.6028). Additionally, the mean presence of rust in MCP trees in MCP/AL stands was not significantly different from the mean presence of rust in MCP trees in monoculture (F-ratio (1, 12) =0.0642, p=0.8043) (Figure 14).

The mean presence of ramicorn branching in MCP trees in MCP/WV3 stands was 0.281 with a standard error of 0.053. The mean presence of ramicorn branching in MCP trees in MCP/AL stands was 0.278 with a standard error of 0.053. The results from the least square mean contrasts suggest that the mean presence of ramicorn branching in MCP trees in MCP/WV3 stands was not significantly different from the mean presence of ramicorn branching in MCP trees in MCP/AL stands (F-ratio (1, 12)=0.0777. p=0.7851). The mean presence of ramicorn branching of MCP trees in MCP/WV3 stands was not significantly different from the mean presence of ramicorn branching of MCP trees in monoculture (F-ratio (1, 12) =0.2810, p=0.6057). The mean presence of ramicorn branching of MCP trees in MCP/AL stands was not significantly different from the mean presence of ramicorn branching of MCP trees in monoculture (F-ratio (1, 12) = 0.0632, p= 0.8058) (Figure 15).

The mean presence of forking in MCP trees in MCP/WV3 stands was 0.077 with a standard error of 0.022. The mean presence of forking in MCP trees in MCP/AL stands was 0.063 with a standard error of 0.022. The results from the least square mean contrasts suggest that the MCP trees in MCP/WV3 stands was not significantly different from the mean presence of forking in MCP trees in MCP/AL stands (F-ratio(1, 12)= 0.2075, p=0.6569). The mean presence of forking in MCP trees in MCP/WV3 stands was not significantly different from MCP trees in monoculture (F-ratio (1, 12) =1.5131, p=0.2422). Additionally, the mean presence of forking in

MCP trees in MCP/AL stands was not significantly different from MCP trees in monoculture (F-ratio (1, 12) = 0.6000, p=0.4536) (Figure 16).

The mean quality rating of MCP trees in MCP/WV3 stands was 3.00 with a standard error of 0.17. The mean quality rating of MCP trees in MCP/AL stands was 2.95 with a standard error of 0.17. The results from the least square mean contrasts suggest that the mean quality rating of MCP trees in MCP/WV3 stands is not significantly different from the mean quality rating of MCP trees in MCP/AL stands (F-ratio (1, 12) = 0.0335, p=0.8578). The mean quality rating of MCP trees in MCP/WV3 stands is not significantly different from the mean quality rating of MCP trees in monoculture (F-ratio (1, 12) = 0.1178, p=0.7374). Additionally, the mean quality rating of MCP trees in MCP/AL stands is not significantly different from MCP trees in monoculture (F-ratio (1, 12) = 0.2770, p=0.6083). A contingency analysis of quality ratings indicated that for MCP trees in MCP/WV3 stands, 0% was rated at 0, 6.28% were rated at 1, 22.87% were rated at 2, 44.84% were rated at 3, 15.25% were rated at 4, and 10.76% were rated at 5. For MCP trees in MCP/AL stands, 0% was rated at 0, 3.57% were rated at 1, 22.32% were rated at 2, 52.23% were rated at 3, 18.75 were rated at 4, and 3.13% were rated at 5 (Figure 17). The Chi-square analysis indicated that there was a non-random distribution of stem quality values by treatment and genotype (χ^2=118.016, p<0.0001).

The volume of MCP trees in MCP/WV3 stands ranged from 0.0061 to 0.0727 cords per tree, with a least square mean of 0.0359 cords per tree and a standard error of 0.0019 cords. The volume of MCP trees in MCP/AL stands ranged from 0.0031 to 0.0724 cords per tree, with a least square mean of 0.0254 cords per tree and a standard error of 0.0019 cords. The volume of WV3 biomass trees in the MCP/WV3 stands ranged from 0.0012 to 0.0583 cords per tree, with a least square mean of 0.0268 cords per tree, and a standard error of 0.0019 cords. The volume of

AL biomass trees in the MCP/AL stands ranged from 0.0029 to 0.0585 cords per tree, with a least square mean of 0.0254 cords per tree, and a standard error of 0.0019 cords. The results from the least square mean contrasts suggest that the mean volume of MCP trees in MCP/WV3 stands was not significantly different from the mean volume of MCP trees in the MCP/AL stands (F-ratio (1,13)=0.4968, p=0.4944). The mean volume of MCP trees in MCP/AL stands was not significantly different from MCP trees in monoculture (F-ratio (1, 13) = 3.5164, p=0.0853). Additionally, the mean volume of MCP trees in MCP/WV3 stands was not significantly different from the mean volume of MCP trees in monoculture (F-ratio (1, 13) = 1.3697, p=0.2646). When compared to MCP monocultures, the WV3 biomass trees in MCP/WV3 stands had a comparatively smaller volume of wood, albeit marginally not significant (F-ratio(1,12)=4.5721, p=0.0538). However, AL biomass trees in the MCP/AL stands had a significantly lower per tree volume in comparison to MCP trees in monoculture (F-ratio (1,12)= 6.8664, p=0.0224) (Figure 18).

The least square mean stand volume of MCP trees in the MCP/WV3 stands was 10.6943 cords per acre, with a standard error of 0.8381 cords per acre. The least square mean stand volume of WV3 trees in the MCP/WV3 stands was 6.3679 cords per acre, with a standard error of 0.8381 cords per acre. The least square mean stand volume of MCP trees in the MCP/AL stands was 11.3811 cords per acre, with a standard error of 0.8381 cords per acre. The least square mean stand volume of AL trees in MCP/AL stands was 4.9236 cords per acre, with a standard error of 0.8381 cords per acre. The least square mean stand volume of MCP trees in the second, third, fifth and sixth rows of the monoculture (analogous to sawtimber trees in the FlexStands™) was 11.5699 cords per acre, with a standard error of 0.8381 cords per acre. The least square mean stand volume of MCP trees in the first and fourth rows of the monoculture (analogous to the AL and WV3 biomass trees in FlexStands™) was 5.9396 cords per acre, with a standard error of 0.8391 cords per acre. The least square mean contrast results suggest that the mean stand volume of MCP trees in MCP/WV3 stands did not differ significantly from the mean stand volume of MCP trees in the MCP/AL stands (F-ratio (1,15)= 0.3358, p=0.5704). Furthermore, the least square mean contrasts suggest that the mean stand volume of MCP trees in the MCP/WV3 stands did no differ significantly from the mean stand volume of MCP trees in the sawtimber rows in monocultures (F-ratio (1, 16)= 0.5457, p=0.4708). Additionally, the least square mean contrasts suggest that the mean stand volume of MCP trees in the MCP/AL stands did not differ significantly from that of the MCP trees in the sawtimber rows of the monocultures (F-ratio (1, 16)=0.0254, p=0.8754). The least square mean contrasts also suggest that the mean stand volume of the WV3 trees in the MCP/WV3 stands did not differ significantly from that of the AL trees in the MCP/AL stands (F-ratio (1, 16)=1.4851, p=0.2406). Mean stand volume in AL trees in MCP/AL stands did not differ significantly from that of the analogous first and fourth rows of MCP trees in monoculture (F-ratio (1, 16)= 0.7349, p=0.4040). Mean stand volume in WV3 trees in MCP/WV3 stands did no differ significantly from that of analogous first and fourth rows in MCP trees in monoculture (F-ratio (1, 16) = 0.1306, p=0.7225).

The least square mean of stand basal area of MCP/AL FlexStands™ was 103.16 square feet per acre, with a standard error of 5.85 square feet per acre. The least square mean of stand basal area of MCP/WV3 FlexStands™ was 103.59 square feet per acre, with a standard error of 5.85 square feet per acre. The least square mean contrast results suggest that the mean stand basal area of the MCP/WV3 treatment was not significantly different from mean stand basal area of the MCP/AL treatment (F-ratio (1,8) = 0.0026, p = 0.9604). The least square mean contrast results suggest that the mean stand basal area of MCP monocultures was not significantly different from the mean stand basal area of MCP/WV3 FlexStands™ (F-ratio (1, 8) = 0.4067, p=0.5415). Furthermore, the least square mean contrast results suggest that the mean stand basal area of MCP monocultures was not significantly different from the mean stand basal area of MCP/AL FlexStands™ (F-ratio (1, 8) = 0.4747, p=0.5103).

The competition indices of MCP trees planted with AL ranged from 1.907 to 5.057, with a least square mean of 3.014 and standard error of 0.219. The AL trees in the FlexStand treatment had a competition index that ranged from 2.367 to 7.493, with a least square mean of 3.928 and a standard error of 0.219. MCP trees planted with WV3 trees had a competition index that ranged from 1.254 to 9.241, with a least square mean of 3.074 and a standard error of 0.219. WV3 trees in the FlexStand arrangement had a competition index that ranged from 2.211 to 31.202, with a least square mean of 4.494 and a standard error of 0.219. The results from the least square mean contrast indicate that the mean competition index of MCP trees planted with WV3 trees was not significantly different from the mean competition index of MCP trees planted with AL trees (F-ratio (1, 14) = 0.0370, 0.8502). Furthermore, the mean competition index of Al trees in the MCP/AL stands were not significantly different from the mean competition index of WV3 trees in the MCP/WV3 stands (F-ratio (1, 14) = 3.3096, p=0.0903. However, the least square mean contrasts did indicate that MCP trees planted with WV3 trees had a significantly lower mean competition index than MCP in monoculture (F-ratio (1, 14) = 6.3696, p= 0.0243). Similarly, MCP trees planted with AL trees had a significantly lower mean competition index in comparison to the mean competition index of MCP monocultures (F-ratio (1, 14) = 7.3775, p = 0.0167) (Figure 19).

DISCUSSION

Monocultures

The least square means contrast results suggest that the both WV3 and AL monocultures had similar quantitative growth measures. Although MCP monocultures had a comparatively higher rate of survival to WV3 and AL monocultures, it was not significant. This result suggests that all three genetic inputs can endure similar environmental stressors. This is particularly important when considering the MCP trees, as improved trees have been labeled as a potential risk because they theoretically may be susceptible to the same damaging agent due to genetic similarity and could therefore lead to whole stand loss; a situation known as the "breeder's dilemma" (McKeand et al. 2003). Since MCP trees survived at a similar rate as WV3 and AL trees (analogous to wild type genetic variability), the trait of increased vigor of MCP trees did not sacrifice genetic susceptibility of common pests. Furthermore, the results suggest that stand establishment of seedlings with higher genetic input is of equal cost to the land owner. Since mortality is not significantly different in each treatment and comparatively lower in MCP monocultures, the investor could potentially profit from a large return due to comparable and comparatively higher survival rates.

The comparisons of mean DBH of trees suggest that AL, WV3, and MCP trees do not differ significantly from each other. Although this result was not expected, the resulting observation suggests that when planted in monocultures, genetic input has no effect on DBH. The results from least square mean comparisons of competition support this argument. Significantly higher levels of competition were observed in monocultures when compared to

FlexStands™, regardless of the level of genetic input. Therefore trees may not have a genetic competitive advantage have when planted with trees of similar genetic inputs. Thus, these findings suggest that monocultures are not as effective of a silvicultural prescription when using genetically improved trees as FlexStands™, as the effect of genetic improvement is inhibited by competition of neighboring trees of the same genetic input.

The least square mean comparisons of mean height-to-live crown suggest that AL, WV3, and MCP trees do not differ significantly from each other when planted in monoculture. This result may be another quantification of the competitive effects within-stand individuals, as the crown ratio (the distance between the height-to-live-crown divided by the total height) has been used as a distant-dependent measure of competition (Biging and Dobbertin 1992). Traditionally, the height-to-live crown ratio to total height has been used in pine plantations to determine when a stand should be thinned, if this ration drops below 35%, the stand should be thinned. Research suggests that closer planting spacing plays a critical role in crown thickness (Akers et al. 2013). While this ratio may be applicable to trees in the monocultures due to the closer planting arrangement and genetic similarity, it may not be applicable the sawtimber trees in the FlexStand™ arrangement due to lower levels of competition.

The least square mean comparisons of total height between monocultures suggest that MCP gown significantly taller than AL trees. However, MCP trees do not grow significantly taller than WV3 trees in monoculture. Additionally, WV3 trees were not significantly taller than AL trees in monoculture. These results suggest that WV3 trees may be able to provide more competitive height growth for MCP trees and may promote higher quality sawtimber for sawtimber trees in FlexStands™. Since MCP trees did not differ significantly from WV3 trees in total height, then WV3 tree may provide a more competitive environment for MCP trees in a

FlexStand™ arrangement. WV3 trees would be able to compete for light resources with MCP trees, promoting upward growth, self-thinning, and would also limit lateral growth by shading lower branches, thereby discouraging the proliferation of co-dominant branches and stem forks. In contrast, AL trees may become overtopped by MCP trees, resulting in two negative consequences for FlexStands™. First, the two adjacent, co-dominant rows of sawtimber trees acquire uneven shading and begin to lose quality growth form. Second, the AL biomass trees become suppressed and cannot provide comparable pulpwood volume. Asymmetric growth in loblolly pine due to genotype and family differences has been observed to shift crop ideotypes into competition ideotypes (Staudhammer et al. 2009).

The least square mean comparisons of incidence of infection by fusiform rust suggest that there were no significant differences in rust infection between monocultures of AL, WV3, and MCP. While this is contrary to the original hypothesis and to advertised claims made by ArborGen, the literature surrounding rust infection in full-sibling families of loblolly pine suggest that the effects of the genetic inputs are additive, as there are multiple gene locations for different methods of rust resistance, and independent of growth traits (Isik et al. 2003, Li et al. 2006, Cumbie et al. 2012). Therefore, while the MCP monocultures did exhibit some significantly larger growth characteristics, the increased growth is not indicative of increased resistance to fusiform rust. Also, due to the additive effects of multiple gene locations for rust resistance, phenotypic expression of resistance may not have been apparent in some individuals. If the MCP trees in monoculture possessed two genes for rust resistance, perhaps the one resistance gene possessed by the AL, WV3, and MCP (inherited from the mother) was expressed, but the environmental conditions were not such that the second gene (supposedly inherited from the father in MCP trees) was expressed.

The least square mean comparisons of incidence of ramicorn branching suggest that MCP monocultures had significantly less incidence of ramicorn branching than both AL and WV3 monocultures, while WV3 trees and AL trees did not have significantly different incidences of ramicorn branching. The observed results were congruent with the hypothesis that MCP trees would have significantly less incidence of ramicorn branching than WV3 and AL trees, but was incongruent with the hypothesis that WV3 trees would have significantly less ramicorn branching than AL trees. Evidence in literature supports these findings, suggesting that open-pollinated trees had higher incidences of ramicorn branches in comparison to full-sibling trees, as well as clones before and after fertilizer treatments (McKeand et al. 2006, Stovall et al. 2011). This is important when considering this experiment, as fertilizer and hardwood control treatments were applied to the stand. In addition, the resistance to ramicorn branching is important when considering the FlexStand™, as spacing will be further apart, and row thinning provides an increase in sunlight for crop trees, giving potential for branching defects.

The least square mean comparisons of incidence of forking suggest that MCP monocultures had significantly less incidence of forking compared to AL monocultures, but did not have significantly less forking when compared to WV3 monocultures. Additionally, the incidence of forked stems in WV3 monocultures was not significantly different from the incidence of forked stems in AL monocultures. Forked stems result in the decrease in the volume of merchantable timber, as well as decreases timber value. Staudhammer et al. found similar results in a pure versus mixed planting of loblolly and slash pine families (2009). However, it seems that forking also varies by family and environment, as full-sibling trees similar to the MCP trees in this study were found to have and increased incidence in forking due to its location and fertilizer treatments (McKeand et al. 2006, Stovall et al. 2011). Thus, it is important to consider the family's provenance and treatments when using full-sibling plantings as it can significantly alter growth quality and value.

The Chi-square analysis indicated that there were significant differences between the distributions of quality values with the monocultures. The contingency table suggests that MCP trees had the highest quality trees, with the most values 4 and 5 ratings. WV3 had the second highest frequency of values 4 and 5 ratings, while AL trees had the lowest values of quality, and had the highest frequency of values 2 and 3 ratings. Overall, MCP trees had the highest frequency of highest quality ratings. This coincides with the forking and ramicorn branching results for monocultures, as MCP trees had the lowest incidence of forked stems and ramicorn branches, which depreciate overall timber value by decreasing total number of logs.

The mean volume per tree in MCP monocultures, while not significantly higher than in AL monocultures, was marginally so. Additionally, no significant volume difference existed between MCP and WV3 monocultures. These results suggest that on a per tree basis, AL, WV3, and MCP trees produce comparable amounts of pulpwood in monoculture, and might yield similar amounts of pulpwood when the stand reaches thinning age. In monocultures, MCP and WV3 trees are very similar in growth characteristics, volume, and quality, and more similar several growth characteristics than MCP and AL trees in monoculture. Therefore, WV3 may provide the best biomass tree for MCP sawtimber trees in the FlexStand™ Silvicultural System. Furthermore, based on quality rankings and volume calculations, WV3 trees may provide comparable level of sawtimber. If the plans for the row thinning of a FlexStand™ system were ever changed to low or crown thinning, WV3 trees may provide the more sawtimber-quality trees than AL trees.

At the stand level, MCP monocultures had a significantly higher basal area in comparison to AL monocultures, but not to WV3 monocultures. Additionally, no significant differences were found in the comparison of WV3 monocultures to AL monocultures. A similar trend was observed for stand volume, where MCP monocultures had a significantly higher stand volume in comparison to AL monocultures, but not to WV3 monocultures. Therefore, while individual tree volume was not found to be significantly different between OP and MCP trees, the marginal, non-significant differences between individual tree volumes between the two genetic input levels accumulate at the stand level and lead to significant differences in stand volume.

The comparison of competition indices between MCP, WV3, and AL monocultures were not significantly different from each other. This is probably due to the similarity of genetic input in each treatment. Since there was no significant difference between competition indices in monocultures, but several comparable as well as significant differences in growth measurements, and quality, these results suggest that if planted together in a FlexStand™ Silvicultural System, trees may face different levels of competition due to their genotype and arrangement. For example, MCP trees planted in a FlexStand™ with AL trees or WV3 trees would probably have a lower competition index when compared with MCP trees in monoculture because 1) MCP trees naturally grow taller and can overtop shorter AL trees and 2) the spacing for MCP trees in a FlexStand™ is wider than the spacings in monoculture. Therefore, the FlexStand™ system may be more beneficial to MCP sawtimber trees due to the potential decrease in competition from AL and WV3 trees, as diameter growth is frequently cited as the lowest priority growth dimension when trees are stressed (Smith et. al 1997).

FlexStands™

MCP trees in FlexStands™ did not have significantly different rate of survival, regardless of WV3 or AL biomass trees. Additionally, no significant differences existed between MCP trees in FlexStand™ treatments and MCP trees monocultures. Therefore, the FlexStand™ treatment does not significantly impact survival rates of MCP trees. Furthermore, the lack of significant difference of survival between genotypes and between genotypes within the same treatment suggests that there are no strong genetic or treatment effects on survival. Therefore, it can be concluded that survivorship is strongly influenced microenvironment.

The least square mean comparisons of DBH between MCP trees in MCP/WV3 and MCP/AL FlexStands™ suggest that there were no significant differences between treatments. However, when compared to MCP trees in monoculture, the MCP trees in the MCP/AL FlexStand™ had a significantly higher mean DBH. This finding suggest that the MCP trees in FlexStand™ may experience a significantly lower amount of stress, as allocation of to stem diameter is low priority in many deciduous and evergreen trees (Dickson 1989, Wiley and Helliker 2012). Furthermore, research shows wider diameters are achieved at wider spacings, as well as after thinning, mainly due to increases in light availability (Ginn et al. 1991, Henry and Aarssen 1999). Therefore the wider spacing in the FlexStand™ arrangement with weaker competitors (AL trees) may have resulted in the larger diameter growth of MCP trees.

The least square mean contrasts results suggest that there were no significant differences in height-to-live-crown between MCP trees in the MCP/WV3 FlexStand™ and MCP trees in the MCP/AL FlexStand™. Furthermore, the least square mean contrasts results suggest that mean height-to-live-crown of MCP trees in each FlexStand™ treatment were not significantly different from the mean height-to-live-crown of MCP monocultures. These findings suggest that crown thickness was not significantly different between treatments. Although MCP trees in monoculture had higher levels of competition, both monoculture and FlexStand™ treatment stands had not reached canopy closure. One might expect the crowns of MCP trees in the FlexStand™ treatments to have thicker crowns (indicated by lower mean height-to-live crown) due to wider initial spacings. However, this was not observed. Previous comparisons of full-sibling loblolly pine growth indicate that full-sibling families will have very similar crown growth characteristics, and are classified into crown ideotypes (Adams and Roberts 2013). Therefore, significant genotype effects on crown structure were found in this study. As there were no significant differences in canopy thickness between monoculture and FlexStands™, the MCP trees must be the same ideotype.

The least square mean comparisons of total height suggest that there were no significant differences in total height between MCP trees in MCP/WV3 FlexStands™, and MCP trees in MCP/AL FlexStands™. Furthermore, there were no significant differences between MCP trees in either FlexStand™ treatment when compared to MCP trees in monoculture. This finding follows the same pattern as height-to-live-crown, as MCP trees in FlexStand™ treatments do no face the same level of competition as MCP trees in monoculture. Furthermore, dominant trees in both monoculture and FlexStand™ treatments should reach similar height due to similar genetic makeup.

The least square mean comparisons of rust incidence indicated that there were no significant differences of rust infection between MCP trees in MCP/WV3 FlexStands™ and MCP trees in MCP/AL FlexStands™. In addition, there were no significant differences of rust infection of MCP trees in FlexStand™ treatments and MCP trees in monoculture. This result is intuitive due to the genetic similarity of the MCP trees. These results also suggest that treatment has no effect on rust infection; even though MCP trees in FlexStands™ were interplanted with AL and WV3 genotypes that had comparatively higher rates of rust infection, rust infection in MCP trees in FlexStands™ did not increase in comparison to MCP trees in monoculture.

The least square mean comparison of incidence of ramicorn branching indicated that there were no significant differences between MCP trees in MCP/WV3 and MCP/AL FlexStand™ treatments. While it was hypothesized that ramicorn branching would increase in FlexStands™ due to a decrease in the total number of co-dominant competitors and wider spacing arrangement, this was not the case. In addition, when compared to MCP monocultures, MCP trees in FlexStand™ arrangements did not have significantly different ramicorn branching incidence. Furthermore, the evidence from ramicorn branching of the WV3 and AL monocultures suggest that there was a significantly lower incidence of ramicorn branching in MCP trees in FlexStands™ when compared to WV3 and AL trees in monoculture. Therefore, it can be concluded that there are strong effects of genetic improvement on ramicorn branching. A lower incidence of ramicorn branching would theoretically decrease stem forking as well as increase the total per tree value of MCP trees due to increasing the total volume of merchantable sawtimber by increasing total stem length.

Similarly, the least square mean comparison if incidence of stem forking indicated that there were no significant differences between MCP trees in the MCP/WV3 and MCP/AL FlexStand™ treatments. In addition, when compared to MCP trees in monoculture, the MCP trees in both FlexStand™ had no significant differences in stem forking. Therefore, it can be concluded that the FlexStand™ treatment had no detrimental effect on stem forking in comparison to monoculture. Furthermore, the lack of significant difference in stem forking between MCP trees monoculture and MCP trees in FlexStand™, in addition to the significant difference in forking prevalence between WV3 and AL monocultures, and lack of significant difference between MCP and WV3 monoculture treatments, support the other findings that suggest strong genetic and environmental effects on stem forking (Xiong et al. 2010, 2014). Stem forking has been cited to lower sawtimber volume by decreasing usable sawlogs per tree, as well as compromise wood quality by creating knots (Doede and Adams 1998, Tong and Zhang 2008). While the lack of forking in MCP trees in the FlexStand™ arrangement is desirable for maximizing total sawtimber volume, the presence of forking in WV3 and AL as biomass trees in the FlexStand™ does not necessarily present a decrease in timber value. Since these biomass trees will be thinned for pulpwood, wood quality and forking is not a primary concern. However, if these biomass trees did not produce comparable volumes of pulpwood as compared to MCP trees, then the FlexStand™ might not be a viable silvicultural system compared to monoculture.

The Chi-square analysis of quality ratings suggests that there were significant non-random distributions of stem quality by genotype and treatment. The MCP trees in the MCP/WV3 FlexStands™ treatment had the highest proportion of trees rated at 5, while MCP trees in the MCP/AL FlexStands™ had the second highest proportion of trees rated at 4. MCP trees in the MCP/AL FlexStands™ had the highest proportion of trees rated at 4, while MCP trees in the MCP/WV3 FlexStands™ had the second highest. Overall, MCP trees in the MCP/WV3 FlexStands™ were of higher quality when compared to MCP trees in the MCP/AL FlexStands™. This result is important because the quality ratings can determine the end use of these crop trees. Therefore, MCP trees planted in the MCP/WV3 have a statistically higher proportion of trees that will be used for high-quality sawtimber, and while the MCP trees in the MCP/AL FlexStands™ have a comparable proportion of trees rated 4 and 5, these treatments also have a higher proportion of lower quality ratings (1-3), where the end use is mostly pulpwood. While the differences in these proportions may not be statistically significant, there may be an economically significant difference in these proportions.

The least square mean contrasts suggest that there were no significant differences in per tree volume between MCP trees in MCP/WV3 FlexStands™ and MCP/AL FlexStands™. Furthermore when compared to MCP monocultures, the per-tree volume of MCP trees in both FlexStand™ treatments was not significantly different. Perhaps the most interesting result from the analysis of volume was that WV3 biomass trees in the MCP/WV3 treatment produced similar volumes of wood as MCP trees in monoculture while AL biomass trees in MCP/AL treatments produced significantly lower volume of wood than MCP trees. This result suggests that FlexStands™ planted with biomass rows of WV3 quality trees may be a favorable economic option for pine plantations in comparison to MCP monocultures.

However at the stand level, there were no significant differences between basal area of MCP monocultures with MCP/AL or MCP/WV3 FlexStands™ treatments. Similarly, stand volume was not significantly different between MCP mono cultures and FlexStands™. These results suggest that while MCP trees produce more wood volume per tree in comparison to AL trees in the FlexStand™ treatments, these differences in wood volume are not significant at the stand level. Therefore, the FlexStand ™ Silvicultural System yields comparable volumes of pulpwood and sawtimber at the stand level in comparison to monocultures.

The least square mean contrast of competition indices indicated that there were no significant differences in competition between MCP trees in the MCP/WV3 FlexStand™ and MCP trees in the MCP/AL FlexStand™. There were, however, significantly lower competition indices between the monoculture treatments and the FlexStand™ treatments. This result can be explained both the further spacing in the FlexStand™ treatments versus the monocultures, as well as the difference in DBH between the biomass trees and sawtimber trees in the FlexStand™ treatments. Overall, MCP trees in the FlexStand™ treatments experience less competition for sunlight. Therefore, it can be concluded that these sawtimber trees in the FlexStand™ may be less stressed than trees in monoculture. This may explain why MCP trees in the MCP/AL FlexStand™ treatments had a significantly higher mean DBH as compared to MCP trees in monoculture. While the differences in mean volume between monocultures and FlexStands™ were not found to be significant, this study was done at the end of the ninth growing season, therefore the volumes by treatment may change once the stands are thinned.

In conclusion, the FlexStand™ Silvicultural System can be a more economically viable option for land owners in comparison to monoculture of the same genetic family. FlexStands™ were comparatively very similar in the quality and volume of wood produced in MCP monocultures, and higher in wood quality in comparison to WV3 and AL trees in monoculture. Furthermore, landowners may be able to manipulate spacing and genetic input to decrease levels on competition and increase diameter growth. The lack of significant differences in volume production through the ninth growing season supports the idea that FlexStands™ are a better economic choice to monoculture, they produce the same volume of wood and cost less to establish due to the lower prices of the lower quality of seedlings. While the MCP/WV3 FlexStands™ appeared to produce the highest proportion of highest quality trees, there was a trade-off between tree quality and diameter. While the MCP/AL produced the largest diameter of MCP trees would result in an overall higher volume of sawtimber trees, the use of the AL trees might result in a higher proportion of low quality trees. In addition, the height difference between MCP and AL trees may pose a problem, as the MCP may be dominant and therefore may be more likely to develop co-dominant branches. In comparison, the height of WV3 trees was not significantly different from MCP, thus the WV3 trees may become co-dominant, thereby decreasing co-dominant branching and increasing sawtimber volume and quality.

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